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PHYSICAL REVIEW.

ON THE GROWTH AND DECAY OF COLOR SENSATIONS IN FLICKER PHOTOMETRY.

By M. Luckiesh.

Introduction.

NOTWITHSTANDING the extensive investigations in heterochromatic photometry the photometrician is still unable to equate brightnesses widely different in color with surety. This is due chiefly to the fact that the two practical methods of photometry—the flicker and the direct comparison methods—do not give concordant results. It is therefore necessary besides establishing an "average eye" to determine which method shall be the standard.

Since the flicker photometer was first proposed as a means of overcoming the difficulties attending a large color difference in photometry, it has won many supporters. But in the light of the work that has been done recently it is plain that those who had accepted the flicker photometer had done so before it had been thoroughly investigated. H. E. Ives[1] has perhaps investigated the two practical methods of photomery in parallel more extensively than any other investigator. Among other interesting data gathered in that investigation it was shown that the flicker method was not subject to the Purkinje effect but to a reversed effect. The writer[2] verified this and incidentally showed that the ratio of a red light to that of a blue-green light as measured was far different depending upon the method. In the present work it was found after balancing a red light and a blue-green light individually against total tungsten light by the direct comparison method, that the intensity of the red light must be reduced to 55 per cent. of its foregoing value in order to balance by the flicker method the foregoing intensity of the blue-green light. This result agrees closely with that obtained in the

[1] Phil. Mag., 1912.

[2] Electrical World, March 22, 1913; London Illuminating Engineer, Vol. 6, p. 119.

previous work. Ives's data show this difference in the results by the two methods although it was not discussed or pointed out in the original paper. This difference and the fact that the flicker photometer is subject to a reversed Purkinje effect are sufficient to show the importance of investigating the possible causes for the discordance in the results by the two methods. It is apparent at once that the physiological phenomena occurring in the two methods are not wholly the same, for only in the direct comparison method is simultaneous contrast effective. Further, the flicker method is probably complicated by after images and the different rates of growth and decay of the various color-sensations.

APPARATUS.

An apparatus was constructed so as to include both a flicker and a direct comparison photometer in such a manner that by intercomparison certain data could easily be obtained without introducing uncertainties which might arise in using two instruments. The apparatus is shown diagrammatically in Fig. 1. The photometer consisted of a two-part

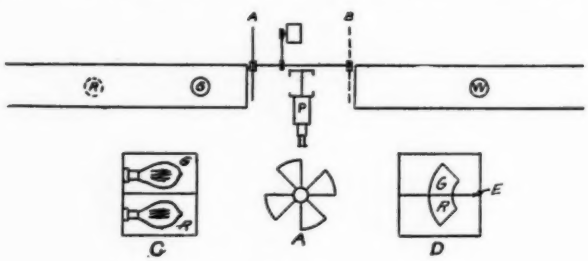

Fig. 1.

Combined Flicker and Direct Comparison Photometers.

field (a circular field about 10°, bisected vertically) one side of which could be converted into a flicker photometer field. Direct comparison could therefore be made of a flickering field against a steady field or the instrument could be used either as a flicker photometer or a direct comparison photometer. *G* and *R* are lamps movable on a two-compartment track whose cross section is shown at *C*. *D* is an end view of the compartments near the sector disk *A*. At *G* and *R* in *D* are placed respectively a blue-green and a red glass over ground opal glasses. These colored glasses whose transmission curves are shown in Fig. 2 were purposely selected nearly complementary to each other in order that little color difference would remain when the lights were mixed and compared with the tungsten standard light *W*. The sector disk *A* rotating about the center *E* causes one side of the photometer field to be a flicker photometer

field. The sector disk (50 per cent. opening) was covered with black velvet to eliminate reflected light. Tungsten lamps at W were used as standards. The lamp G was kept in one position throughout the measurements, the balances being obtained by moving either R or W.

Much of the data obtained by means of this apparatus was for purposes of verification of the outstanding difference in the results by the two methods and a study of the fundamental axioms which must underlie any correct method of photometry. Not all of these data are reported

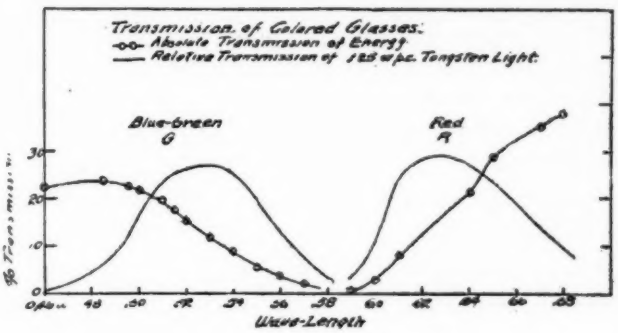

Fig. 2.

in the present work, some of it having been reserved until other observations can be made. However in order to illustrate more fully the adaptability of this apparatus to the general problem a regular series of observations will be described. First G was set at a certain position and with the sector disk removed a series of settings were made in which G was balanced against the standard lamp W by the direct comparison method. W was set at the mean value thus obtained and R was balanced against it. R was then set at the mean value just obtained and with G also lighted and with the 50 per cent. sector A now rapidly rotating this mixture was balanced against W by varying the position of W. Next R was balanced against G by the flicker method by varying the position of R. Finally R was balanced against W with a red glass interposed between the latter and the photometer, the balance being made by varying the position of W. It was then possible to match G against R by the direct comparison method. The mean values of a number of such series yielded interesting information regarding the two methods.

The measurements were made in all cases unless otherwise noted, at an illumination of about five meter-candles upon the photometer screen computed from the position of W. In the former work[1] with the same photometer it was found that at an illumination above one meter-candle

[1] Electrical World, March 22, 1913; London Illuminating Engineer, Vol. 6, p. 119.

no complications arise from the Purkinje or reversed effect; that is both methods give the same results as at higher illuminations. However at an illumination somewhat lower than one meter-candle on the photometer screen results varied considerably from the values at higher illumination.

ON MIXING COLORED LIGHTS BY THE FLICKER METHOD AND BY SUPERPOSING STEADY LIGHTS.

An experiment was performed to ascertain if there was any difference in brightness on mixing the two colored lights by the flicker method and by superposing the steady lights. The colors being nearly complementary to each other the color difference in these measurements was small. When the colored lights were mixed by means of a sector disk the speeds of the latter were slightly above and below that at which flicker vanished. The sector disk was also rotated at a very high speed and finally was taken out and the lights permitted to mix by superposition. In all cases the comparison was made against W with the same slight color difference. Practically identical results were obtained in all cases showing that there was no difference in brightness when R and G were mixed by superposing the two colored lights or as in the flicker method providing the flicker was not more than barely apparent. This supports the validity of Talbot's law for colored lights.

ON THE GROWTH AND DECAY OF COLOR SENSATIONS.

It has long been known that the retina responds at different rates to lights of different color. Broca and Sulzer[1] have investigated the growth of luminous sensation for lights of various colors. Some initially far overshoot their final value while others barely exceed their final steady value. It was found that red, white, and blue overshoot considerably while green overshoots scarcely at all indicating that with green light there is either a very slight lag of fatigue behind impression or very slight retinal fatigue. A successful attempt was made to determine the maximum values of flickering lights at various flicker frequencies. A flickering field illuminated by R (Fig. 1) was compared with a steady red field and the maximum brightness of the flickering field was measured throughout a wide range of sector speeds. The same was done with the blue-green light G. In both cases the intensities of R and G were those resulting from a balance against W by the direct comparison method. These were the mean values of a large number of observations. The curves in Fig. 3 show the values of the maximum brightnesses of the

[1] Comptes Rendus, 1903, p. 137, 977, 1046.

two flickering colored lights (each flickering against darkness) at various flicker frequencies. It is to be noted from these curves that flicker disappears at a lower speed for the blue-green light G than for the red light R. With the intensity of G unchanged from its foregoing value R was balanced against it by the flicker method. The speed of the sector disk necessary in this case was 12 cycles per second as indicated in Fig. 3. It will be noted that the maximum brightness of R at this speed is greater than that of G. Of course the flicker in each case shown in the curves was R or G against black while with the flicker photometer it was R against G. It must not necessarily be supposed that when the intensities of R and G are such that their flickers against black disappear at the same speed, that they will balance each other by the flicker method. However it appears from Ives's data and also from the writer's data that this is nearly if not absolutely true for the conditions under which these experiments were made. The results of this experiment combined with

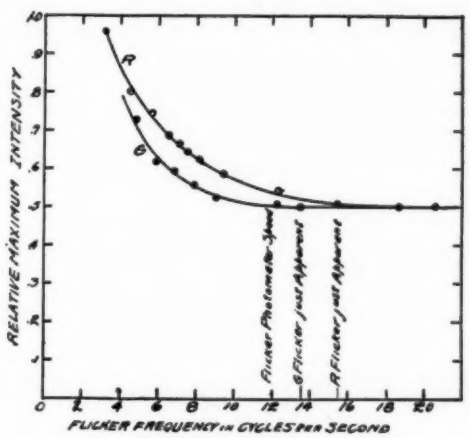

Fig. 3.

Maximum Brightness of a White Surface Illuminated by a Flickering Colored Light.

those which follow indicate quite strongly why the intensity of R when balanced against G by the flicker method must be decreased from its value as determined by a direct comparison measurement. The results shown in Fig. 3 were verified by many tests and while the eye seemed to vary in its sensibility to flicker very consistent results were obtained considering the difficulty in making such observations. An attempt was made to obtain the minimum brightness of the flickering lights but it was found that the maximum brightness was always so distracting in its effect that attention could not be riveted upon the minimum value. The curve representing minimum values would obviously start at zero

and finally reach a steady value which would be, as in the case of maximum values, one half of the steady maximum value. The latter statement assumes the validity of Talbot's law for colored lights which was verified in this work. The effect of change of intensity is shown in Fig. 4. Here the intensities of the red and blue-green lights are approximately those determined by the mean of the results obtained by the two methods. It is seen that at the higher illumination there is an overshooting of the steady value which is taken as unity with the sector stationary and open. This overshooting is greater for the red light than for the blue-green

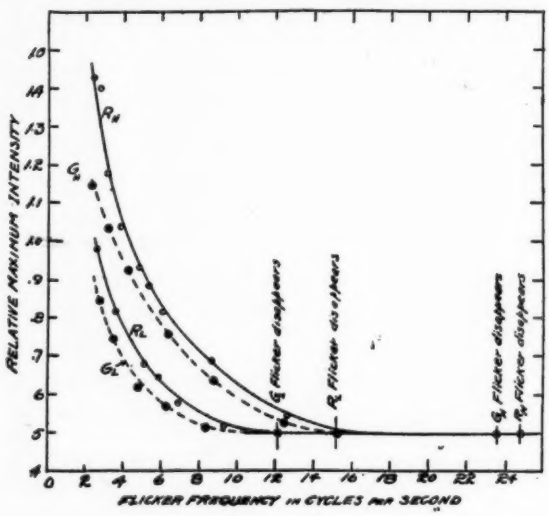

Fig. 4.

Showing the Effect of Intensity on the Maxima of a Flickering Light. Full Line Represents Red Light. Broken Line Represents Blue-Green Light. Subscripts Indicate High and Low Intensities.

light. As the illumination decreases the over-shooting becomes less marked. This is to be expected from the work of Broca and Sulzer which work however was done apparently in a different manner and without special consideration from the standpoint of flicker photometry.

Effect of After-images.

An arrangement, which is shown diagrammatically in Fig. 5, was devised to study the effect of after-images. Steady sources G_1 and R_2, respectively blue-green and red in color, as used throughout the work, were arranged to illuminate opposite sides of the photometer screen. Illuminations due to R_1 and G_2 of the same colors as the foregoing lights were arranged to be flickered by means of identical 50 per cent. sector disks, S_1 and S_2, rotating on the same shaft. By this means it was possible

to flicker red light from R_1 on a steady blue-green field due to G_1 and compare this total brightness with that resulting from flickering blue-green light from G_2 on a steady red field due to R_2.

All observations were made without color differences. The procedure was as follows: R_1 and G_2 were taken the same as previously determined by the direct comparison method, then R_1 was balanced against R_2 with G_1 and G_2 extinguished, the sectors being open and stationary. Next R_1 and R_2 were extinguished and G_1 was balanced against G_2. Finally with all four lights turned on and with the sector disks rotating at a speed such that flicker was barely apparent the photometer field remained balanced as might be expected. However as the speed was reduced the side of the photometer field upon which R_1 was flickering apparently became much brighter; at least the maximum value of the brightness was considerably greater. Flicker upon this side of the photometer was very violent while upon the other barely apparent. A great reduction in the speed was necessary before the flicker upon the other side became very marked. In fact the illumination on the side where the blue-green light flickered appeared quite uniform as the speed was reduced long after the side on which the red light flickered, became violently agitated. This same phenomenon was noticeable to a much less degree after the steady lights were extinguished.

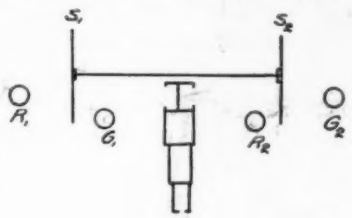

Fig. 5.

Apparatus for Superimposing a Flickering Colored Light Upon a Steady Light of Different Color.

Next, by combining certain features of the apparatus shown in Figs. 1 and 5, actual measurements were made of the maximum brightness attained by the red light flickering upon the steady green field and vice versa, the comparison source being a clear tungsten lamp W. The results are shown in Fig. 6. The intensities of the steady lights were twice the mean values of the flickering lights. The flicker photometer speed at this illumination would be about thirteen cycles per second in comparing the particular red and blue-green lights. When R and G were of such values as determined by the flicker method the above effects would have been greatly decreased in magnitude. In fact one could not be certain that under these conditions there was any difference in the flicker of the two fields. This experiment gives a strong clue to the reason for decreasing the intensity of the red light when it is balanced by the flicker method against blue-green light. The much greater agitation of the field consisting of a flickering red light and a steady blue-green light points very strongly to the conclusion that the red light is weighted

more by the flicker method than by the direct comparison method because in order to obtain a balance the intensity of the red light must be diminished so that the flicker of *R* and *G* disappear at about the same speed. These data shown in Figs. 3 and 6 represent extreme experiments between which will be found the operation of the flicker photometer.

The difference in the rate of growth of sensation stimulated by lights

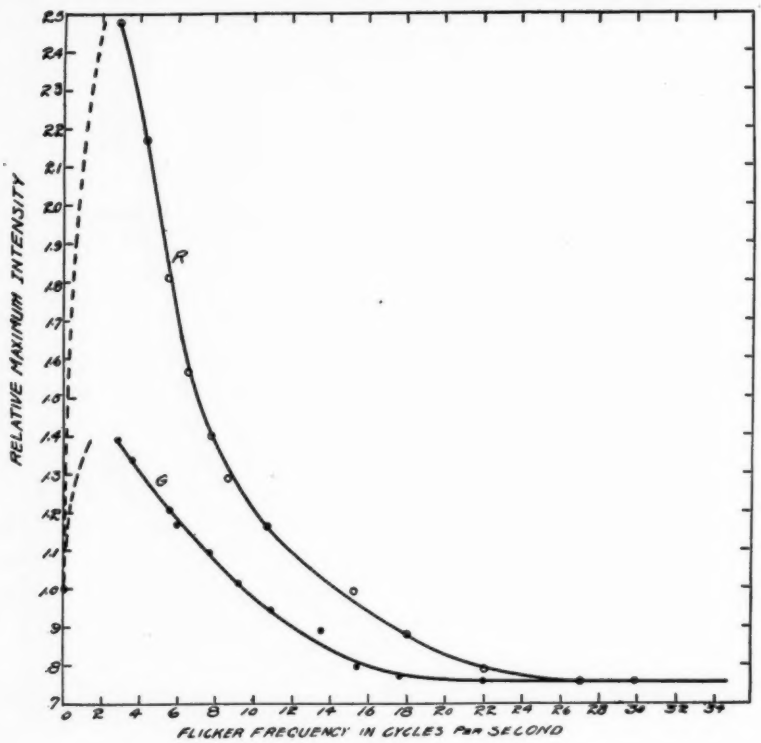

Fig. 6.

Maximum Brightness of a White Surface Illuminated by Superimposed Red and Blue-Green Lights, One of Which is Flickered. *R* Indicates Red Flickering on Steady Blue-Green Field. *G* Indicates Blue-Green Flickering on Steady Red Field.

of different color suggests the possibility that flicker photometers differing in design might not yield concordant results. The flicker photometer shown in Fig. 1 is of such nature that when balancing red light against blue-green light the color of the photometer field varies gradually from red through white to blue-green then to white and so on. In most flicker photometers the stimulus changes abruptly from one color to another. In the previous work[1] a Schmidt and Haensch flicker photometer was used. With that instrument the results obtained were not exactly the same as those obtained by the flicker photometer used in this

[1] Electrical World, March 22, 1913; London Illuminating Engineer.

work and reported in the first part of this paper. The writer cannot say that the difference in the results (which was not great) is due to the difference in the design of the photometers. However the effect of contour or wave-form of flicker may be of importance in flicker photometry.

ON VANISHING-FLICKER FREQUENCY.

The vanishing-flicker frequency (often referred to as critical frequency) is that frequency at which flicker vanishes when the light is rapidly alternated with darkness. This has long been known to vary with the intensity of the flickering light or brightness of the target. Kennelly and Whiting[1] state that "the vanishing-flicker frequency does not depend upon the mean illumination on the target: or at least only to a relatively small degree. It depends on the maximum and minimum cyclic illumination." They also conclude that "the vanishing-flicker frequency does not depend appreciably upon the wave-shape of flicker, that is, upon the manner in which the illumination varies in passing between the maximum and minimum cyclic values." As the apparatus diagrammatically shown in Fig. 1 readily lent itself to a study of this problem some experiments were carried out in order to determine whether wave-form of flicker is sufficiently important to bear investigation in regard to its effect in flicker photometry. The experiments were made with clear tungsten light. It has been established by Porter[2] that $f = k \log I + p$ represents the relation between critical frequency, f, and the illumination, I, where k and p are constants. In Fig. 7 the writer's results obtained with flickering lights of different contours of flicker. In cases a, b, and c the maximum, minimum, and mean cyclic values of illumination were respectively the same. In case d, for a given mean cyclic illumination the maximum illumination was 4.5 times that in cases a, b and c. The mean illumination on the photometer screen in meter candles is plotted logarithmically. Similar to what was found by Porter one straight line relation is seen to hold down to a low illumination where another straight line relation seems to begin. The location of this point of course depends upon the absorption of light in the photometer used and in these cases seems to depend somewhat upon the contour of flicker although the points where the lines of lesser slope begin are not well defined. The data shows that critical frequency varies even with equal values of maximum and minimum illumination. Further on comparing a, b and c it is seen that the contour of flicker determines the critical frequency. On comparing d with the other cases it is seen that the critical frequency at a given mean illumination is much higher when the period of darkness is greater or

[1] Proceedings of the National Elec. Light Assn., 1907.

[2] Proc. Roy. Soc., LXXIX., 1902, p. 313.

where the maximum value is greater. Further it is seen that the shorter the period of darkness the lower is the critical frequency at a given mean illumination when the maximum and minimum values of the flickering lights are the same. In other words the more abruptly does the stimulus rise in value the greater is the critical frequency. It is thus seen that the

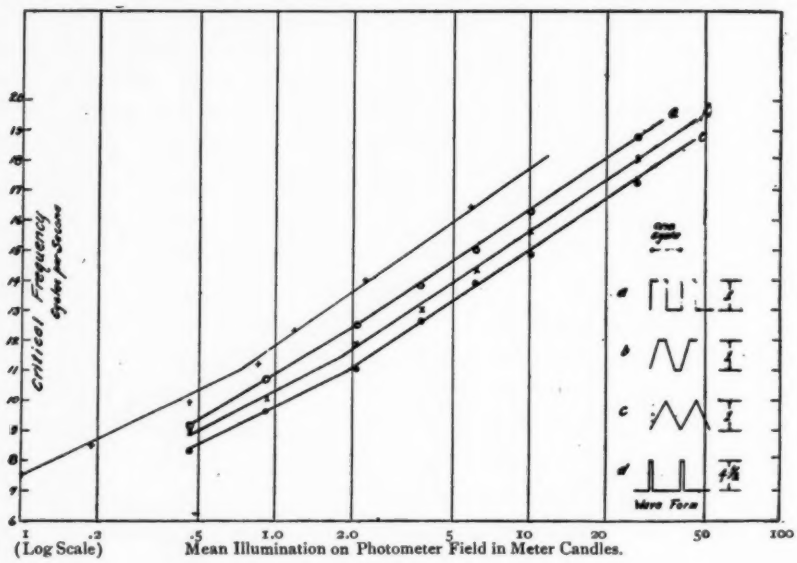

Fig. 7.

Effect of Wave-Form of Flickering Lights on Critical Frequency.

contour of flicker has a highly important bearing upon the critical frequency. These results contradict the statements quoted from Kenelly and Whiting. From these data it is seen that critical frequency is influenced by the contour of flicker, and the maximum, minimum and mean values of illumination during the cycle.

SUMMARY.

1. Red and blue-green lights add in the same manner whether by direct superposition or by alternately flickering them as in the flicker photometer when the speed is not lower than that at which flicker is barely apparent.

2. The maximum value of a flickering red light is always greater than that of a blue-green light flickering in the same manner and at the same frequency, when the steady values of the intensities of these two lights are those determined by a direct comparison balance. This is very much more marked when a red light is flickered upon a steady blue-green field than when a blue-green light is flickered upon a steady red field. In the latter case the agitation of the field which consists of a red light flickering

upon a steady blue-green field is much more marked than in the opposite case at practically all speeds below the critical-frequency speed. This seems to account for weighting red light more than blue-green light by the flicker method than by the direct comparison method.

3. The speed at which flicker disappears is much higher for the red light in the foregoing cases just noted than for blue-green light of the same intensity as determined by comparing the two lights by the direct comparison method.

4. It is shown that the contour of flicker has considerable influence upon the critical frequency which is the frequency at which flicker vanishes at a given illumination when the light is alternated with darkness.

The writer is indebted to Mr. Leonard Krill and Mr. Abe Shapero for assistance in the experimental work and Mr. H. MacMullen for the preparation for the drawings.

Appendix.

An interesting experiment the results of which point with favor to the flicker photometer is found in comparing lights of the same color but differing in spectral character. By means of dyes two yellow lights identical in color were produced. One was a pure yellow while the other was a subjective yellow composed of green and red light. These were balanced by the direct comparison method very readily because there was no color difference. When balanced by the flicker method it was found that the results were the same as obtained by the direct comparison balance within at least one per cent. The same experiment was performed with "white" lights, one being the continuous spectrum light from a tungsten lamp, the other being made by mixing red and blue-green lights. Here again the results were practically the same by the two methods. These experiments indicate quite strongly that the flicker photometer is not effected by the difference in the rates of growth and decay of color sensations. Of course other combinations of colored lights to produce two lights of the same color but differing in spectral character might give different results by the two methods. If no differences are found it might be fair to assume that the flicker photometer measures true brightness and that the differences in the results by two methods are entirely attributable to the effect of simultaneous contrast and other phenomena involved in the direct comparison method. The latter method does not satisfy the fundamental axioms already mentioned which is a serious cause for looking upon this method with disfavor when seeking a reliable method of photometry for the standardization laboratory. In summing up the evidence it appears that for a laboratory method the balance is in favor of the flicker photometer.

THE MAINTENANCE OF VIBRATIONS.

BY C. V. RAMAN.

PART I.

IN my paper on "Some Remarkable Cases of Resonance" published in the PHYSICAL REVIEW for December, 1912, I described a new class of forced vibrations which form apparent exceptions to the general principle of resonance, i. e. in respect of which we find systems exhibiting marked resonance under the action of forces whose periods do not necessarily stand to their own in a relation of approximate equality. Of this class, the first type is the well-known case of double frequency exemplified by the form of Melde's experiment in which the vibrations of a stretched string are sustained by the action of a varying tension imposed by a fork having double the frequency of the string. My experiments showed that the vibrations could be maintained in the following cases:

(1) When the frequency of the fork is 2 times that of the string;
(2) When the frequency of the fork is $\frac{2}{3}$ times that of the string;
(3) When the frequency of the fork is $\frac{4}{5}$ times that of the string;
(4) When the frequency of the fork is $\frac{2}{4}$ times that of the string;
(5) When the frequency of the fork is $\frac{2}{5}$ times that of the string;
And so on.

Photographs illustrating the modes of vibration in each of these cases were published with the paper.

Some very interesting phenomena are noticed when a stroboscopic disk is used in observing these types of maintained motion. A Rayleigh synchronous motor on which is mounted a blackened disk with narrow radial slits cut in it is very suitable for this purpose. One of the disks which I use has thirty slits in it, the armature-wheel of the motor having the same number of teeth. The electric current from the self-interrupter fork which maintains the string in vibration also runs the synchronous motor. In making the observations, the stroboscopic disk is held vertically and the string which is set horizontal and parallel to the disk is viewed through the top row of slits, *i. e.*, those which are vertical or nearly so and move in a direction parallel or practically parallel to the string as the disk revolves. It is advantageous to have the whole length of the string brilliantly illuminated and to let as little stray light as

possible fall upon the reverse of the disk at some distance from which the observer takes his stand. A brilliant view is then obtained. Under these circumstances, we see the string in successive cycles of phase along its length, and the peculiar character of the maintained motion in these cases is brought out in a very remarkable way. *The string is seen in the form of a vibration-curve*, which would be identical with those obtained by other methods but for the fact that the amplitude of motion is not the same at all points of the string, being a maximum at the ventral segments and zero at the nodes.

If we use a fork with a frequency of 60 per second, the *free* oscillations of the string should have a frequency of 30 in the case of the first type, 60 in the case of the second, 90 with the third, 120 with the fourth, 150 with the fifth, and so on. With the disk having 30 slits on it we get 60 views per second of any one point on the string, and with the even types of motion, *i. e.*, the second, fourth, etc. the 'vibration-curve' seen through the stroboscopic disk appears single. Figs. 3 and 7 show the curves for the second and fourth types respectively. With the odd types on the other hand, *i. e.*, with the first, third, fifth, etc., *two* vibration-curves are seen, one of which is as nearly as can be seen the mirror-image of the other, intersecting at points which lie or should lie upon the equilibrium position of the string. Figs. 1 and 5 show the curves for the case of the first and third types. The reason why with the odd type we see the vibration-curve double is fairly obvious and forms an excellent illustration of the principles of stroboscopic observation. The double pattern in the case of the third and higher types brings home to the eye in a very vivid and convincing manner the fact that under the action of the variable spring the "amplitude" and "period" of the motion periodically increase and decrease after the manner of "beats."

An interesting variation on the experiment is made by using a disk with 60 slits. We then get 120 views per second and with the even types we get the vibration-curves double, but one of the curves is not the mirror image of the other, the motion not being symmetrical with respect to the position of equilibrium. On the other hand, with the odd types we see the vibration-curves in quadruple pattern, the third and fifth types in particular giving noteworthy effects. Figs 2, 4, 6, and 8 exhibit the patterns obtained in this manner with the first, second, third and fourth types respectively.

Before leaving this subject, it is worth while to remark that the special method of stroboscopic observation described above can be very effectively applied to the study of the vibrations of stretched strings produced or maintained in any other manner, *e. g.*, by bowing or striking.

The vibrational forms for various points over the entire length of the string can all be observed together simultaneously with the apparatus, and this is often a very great convenience. For example, the widely-differing ratios between the forward and backward velocities at various points on a bowed string can all be seen together and compared in one experiment, and the effect of applying the bow at different positions, of reversing its direction of motion, or of removing it altogether and allowing the motion to die away gradually can be very conveniently studied. It is necessary in such work that the string should be tuned to the correct frequency in the first instance (by observation through the stroboscopic apparatus) so that a stationary figure may be obtained.

PART II.

A stroboscopic disk with radial slits mounted on a synchronous motor can be very effectively used in observing the peculiar properties of the small motion at the nodes of a vibrating string described by me in a previous publication in this REVIEW.[1] In this case an arrangement somewhat different from that described in Part I. of the present paper should be used. An electrically-maintained fork maintains the string in oscillation in any convenient number of loops by imposing a *transverse* obligatory motion at one point on it. The current passing through the fork also drives the synchronous motor on which is mounted a stroboscopic disk having just double as many apertures as the armature-wheel has teeth. The disk therefore gives two views of the fork and of the string maintained by it, which are practically stationary provided the point of observation is fixed and the motor is running satisfactorily. In the present case it is essential that the position taken up by the observer or the camera should be quite close to the stroboscopic disk and should be so chosen that the slits through which the vibration is observed are as nearly as possible parallel to the string and move in a direction at right angles to its length. The most convenient plan is to have the string horizontal and the plane of its vibration vertical. The disk should then be set vertically and the observations made through the region of the disk in which the radial slits are horizontal or practically so. By changing the point of observation, successive phases of the motion and the periodic "travel" of the "nodes" over a large horizontal range seen under the intermittent illumination can all be observed at leisure.

For photographic work, the camera employed is brought up close behind that one of the slits on the disk which is horizontal. The lens is stopped down by a plate which has a rectangular slit cut in it so as to

[1] "The Small Motion at the Nodes of a Vibrating String," PHYS. REV., March, 1911.

correspond with those on the disk. By racking up the lens-front of the camera by successive small distances till it has moved through a length equal to that between contiguous apertures on the disk, a complete set of photographs can be obtained on one plate showing successive stages of the motion of the string. Fig. 9 reproduces a photograph obtained in this manner and showing the cycle of changes in 13 stages. It will be seen that the point of intersection or "node" which is first in the center moves off to one side of the field, first slowly and then more quickly, till after the lapse of a time which can be seen to be exactly half the period of the cycle, it has gone well off the plate and the positions of the string seen in the photograph are sensibly parallel. Direct observation shows that the point has moved off to a great distance, in fact to a distance equal to half the length of a ventral segment. It simultaneously appears at an equal distance on the other side and moves in from that direction first quickly and then more slowly till it reaches the center again and the cycle is complete.

From Fig. 9, it is quite obvious that the phase of the small motion at the node differs by quarter of an oscillation from that of the large motion on either side of it at a distance.

PART III.

A very neat modification of Melde's experiments can be arranged by attaching one extremity of a fine cotton or silk string to a prong of an electrically maintained fork held so that the string lies in a plane perpendicular to the prongs but in a direction inclined to their line of vibration.[1] In view of the ease with which the experiment is performed and the great beauty of the form of oscillation maintained (this must be seen to be fully appreciated), the following brief discussion of the results may be of interest.

The obligatory motion imposed at one extremity of the string may be resolved into two components, one parallel and the other perpendicular to the string. The two components may be put respectively equal to $\gamma \cos pt \cos \theta$ and $\gamma \cos pt \sin \theta$. The transverse component maintains an oscillation having the same frequency as that of the fork and having an even number of ventral segments when the tension of the string is suitably adjusted. The longitudinal component will then generally be found to maintain an oscillation having half the frequency of that of the fork. The success of the experiment lies in isolating the two vibrations, the frequency of one of which is double that of the other, into perpendicular planes. This is easily secured by a simple little device. The

[1] See PHYS. REV., Vol. XXXII., page 311.

end of the string is attached to a loop of thread which is passed over a prong instead of directly to the prong itself. The result of this mode of attachment is that the frequencies of vibration in the two planes at right angles differs slightly and this has the desired effect of keeping the component vibrations confined to their respective planes, if the tension of the string lies anywhere within a definite range.

If the distance of any point from the fixed end when at rest is x, the transverse components of the maintained motion may be written as under

$$Y = \gamma \sin \frac{\theta R_x}{R_b} \cos (pt + E_x - E_b), \tag{1}$$

vide Lord Rayleigh's Theory of Sound, Art. 134.

$$Z = B \cos \left(\frac{pt}{2} + E\right) \sin \frac{\pi x}{b}, \tag{2}$$

the values of B and E being ascertained from the investigation given in the PHYSICAL REVIEW, Vol. XXXV., page 451. If we exclude any consideration of the motion at points near the nodes of the maintained oscillation, equation (1) may be written in the simple form

$$Y = \gamma \sin \theta \sin \frac{px}{a} \cos (pt + E').$$

If $p/a = 2\pi/b$, (1) and (2) may be written in the form

$$Y = A \sin \frac{2\pi x}{b} \cos (pt + E'), \tag{3}$$

$$Z = B \sin \frac{\pi x}{b} \cos \left(\frac{pt}{2} + E\right). \tag{4}$$

It should be understood that in these equations Y and Z do *not* refer to the coördinates of any point fixed relatively to the string but to the points at which a plane transverse to its equilibrium position cuts the surface generated by the moving string. The distinction is of importance in view of the fact that each point on the string possesses a small longitudinal motion derived from that imposed by the fork and the x coördinate of any point fixed relatively to the string is therefore not itself constant.

In particular cases equations (3) and (4) may be reduced to very simple forms. Thus if $E' = 2E$ and also in the special case when both E and E' are equal to zero

$$\frac{Y}{A} \operatorname{cosec} \frac{2\pi x}{b} = \frac{2Z^2}{B^2} \operatorname{cosec}^2 \frac{\pi x}{b} - 1, \tag{5}$$

FIG. 1.

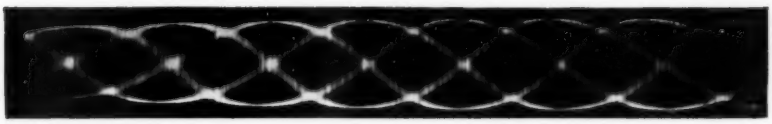

FIG. 2.

FIG. 3.

FIG. 4.

FIG. 5.

FIG. 6.

FIG. 7.

FIG. 8.

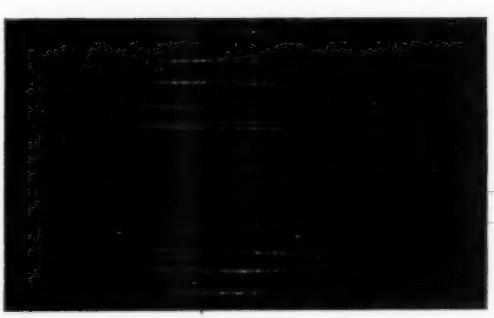

FIG. 9.

C. V. RAMAN.

which is the equation of the surface generated by the moving string, the sections of which by planes perpendicular to the axis of x are parabolic arcs. The curvatures of the arcs are in opposite direction in the two halves of the string. When $E' = 2E + \pi$, a parabolic type of motion should also be obtained. This case can be realized approximately by having the tension of the string as low as possible consistent with the maintenance of the motion. In the intermediate case when $E' = 2E + \pi/2$, the sections of the surface described by the moving string elsewhere than at its center are 8 curves. At the center, the curve is a very flat parabolic arc, as the phase of the small motion at the node differs by quarter of an oscillation from that of the rest of the string.

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CALCUTTA, INDIA.

THE LUMINESCENCE OF KUNZITE.

BY E. L. NICHOLS AND H. L. HOWES.

THAT the variety of spodumene known as kunzite is phosphorescent has been known almost from the day of its discovery. In August, 1903, Geo. F. Kunz[1] described its occurrence and properties and in September of that year Baskerville[2] who was making an exploration of the optical properties of the minerals in the American Museum of Natural History proposed the name of kunzite for this substance and in the course of his description stated that although it showed no sign of fluorescence or phosphorescence when exposed to ultra-violet light, X-rays excited it to a prolonged whitish phosphorescence.

Kunz and Baskerville[3] subsequently tested the luminescence of numerous minerals and reported that kunzite was wonderfully phosphorescent under the action of radium; that ultra-violet light, contrary to Baskerville's first observation, excited certain specimens to prolonged luminescence and that X-rays affected all the crystals of that mineral which were examined.

A writer in Nature, presumably Mr. F. Soddy,[4] speaks of the excitation of kunzite by radium as due chiefly to the β rays and mentions also the powerful excitation obtained by kathodo-bombardment.

Pochettino[5] in his extended investigation of the luminescence of minerals included the spodumenes and in particular certain samples of kunzite. He found this substance feebly fluorescent under the action of light with the emitted rays polarized.

Under the kathode rays he was able to observe a spectrum consisting of a very strong broad band extending from λ .690 to λ .515 and a weak one from .48 to .42. The band of longer wave-length was of protracted phosphorescence while that in the blue disappeared "instantly" upon cessation of the excitation. Pochettino noted further the phenomenon of thermo-luminescence at 235° C.; in which case the rays were not polarized. The power of emission ceased at about 400° C.

[1] Kunz, Science, 18, p. 280 (1903).

[2] Baskerville, Science, 18, p. 303 (1903).

[3] Kunz and Baskerville, Science, 18, p. 769 (1903).

[4] "F. S.," in Nature, 69. p. 523 (1904).

[5] Pochettino, Il Nuovo Cimento (V), 18, p. 245 (1909), and (VI), 1, p. 21, 1911.

It was the purpose of our experiments to study more in detail the location and character of these bands, to seek for the absorption bands which are generally if not universally associated with fluorescence and to determine the law of decay.

FLUORESCENCE.

The crystals at our disposal appeared to be of two varieties: (1) Those with the pink or rose-lilac hue generally considered to be characteristic of kunzite and (2) crystals nearly colorless but with a suspicion of a green- or aqua-marine tint.

Under the action of kathode rays both were strongly fluorescent but the colors differed. The pink crystals glowed with the powerful yellow-red light described by previous observers, which resembles nothing more

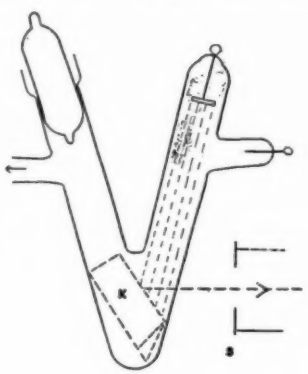

Fig. 1.

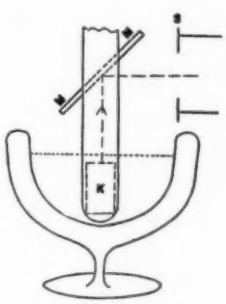

Fig. 2.

closely than the light from some transparent body, as quartz or glass at a temperature of about 900° C. The colorless specimens were of a rose-violet hue.

Observed with a hand spectroscope this difference is seen to be clearly due to the relative strength of the fluorescence bands. In the case of the colorless crystals the blue band is much stronger and its intensity is such as to notably modify the color of the fluorescent light.

The specimen (K) to be studied was placed in a V-shaped vacuum tube as shown in Fig. 1 and the face, bombarded from above by kathode rays, was observed with a spectrophotometer, the slit of which is shown at S.

The strong broad band lying between .7 μ and .5 μ was readily measured spectrophotometrically and was found to have the well known and typical form observed in numerous other fluorescent substances and depicted in previous papers.[1]

[1] Nichols and Merritt, PHYS. REV. (1), Vols. XVIII., XIX. and XXI.

The curve of distribution of intensities (*B*, Fig. 3) is as usual nearly symmetrical but somewhat steeper towards the violet. The well-defined crest is at .590 μ. There is nothing to suggest that it is a composite of overlapping bands.

To determine the effect of cooling which is known in many cases to modify the character of the fluorescence spectrum, the tube was immersed in liquid air to a level above that of the crystal as shown in Fig. 2. In this case observations were made by placing a mirror *M* between the arms of the vacuum tube so as to reflect the fluorescent light, emanating vertically from the crystal, into the collimator slit at *S*.

The appearance of the specimen when thus cooled is distinctly redder to the eye and this impression is verified by the spectrophotometric measurements. The curve (*A*, Fig. 3) which is somewhat narrower, has

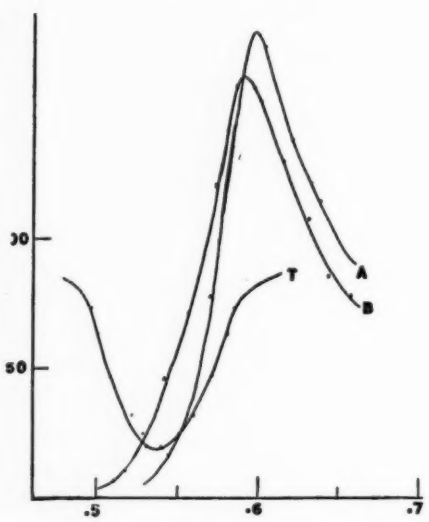

Fig. 3.

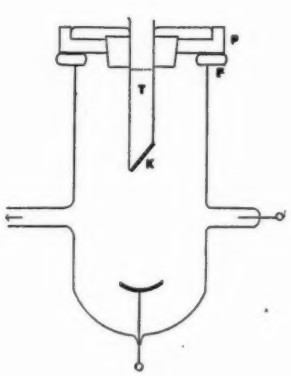

Fig. 4.

its crest shifted towards the red to .598 μ and indicates accession of the longer wave-lengths together with marked diminution on the violet side. There is no indication of even a partial resolution into a group of narrow bands.

That a crystal, thus situated in vacuo within a glass tube and subjected to the heating effect of even a very moderate kathodic bombardment, will be in thermal equilibrium at some temperature considerably above that of the liquid air surrounding the tube is obvious. That this difference of temperature may be more than 100° C. is indicated by previous experience with substances subjected to somewhat similar conditions.

In a case which was described in a paper presented before the American Physical Society, the character of the spectrum afforded a sufficient criterion on which to base this estimate.

A modification of the apparatus enabled us to determine the fact that even at a temperature really approaching that of liquid air no further marked modification in the position or appearance of the band occurred. For this purpose a small piece of the kunzite was powdered and cemented to the outer surface of a test-tube the bottom of which had been softened by heat and obliquely flattened so as to form a convenient target for kathode rays. This test tube was mounted within a vacuum tube of the form shown in Fig. 4 in which P is a cast-iron plate ground to the flange F of an open-mouthed glass tube having a kathode at the bottom. The test tube T was inserted through a rubber stopper fitted to a central opening in the iron plate. When a proper vacuum had been attained liquid air was poured into the test tube cooling the coating of powdered kunzite at K. The fluorescence of K could be observed in the manner previously described and any change in the character of the spectrum noted. The measurements while less satisfactory than those indicated in Fig. 3 were in essential agreement with them.

The fluorescence band of shorter wave-length which begins at .49 μ and extends into the violet, is less favorably situated for study with the spectrophotometer and we contented ourselves with an estimation of its extent and general character by a photographic method. Spectrograms were taken, using both the pink and white crystals, upon two different plates so as to lessen errors due to the selective sensitiveness of the photographic film. The negatives indicated that the same bands were present in both cases but, as had already been noted by visual observations, were of very different relative brightness. The blue band was found to lie between .49 μ and .40 μ with a crest at approximately .432 μ. Since the location of the crest by visual inspection was rather uncertain one of the negatives was measured as to density, step by step at intervals of 1 mm. by means of a photoelectric cell. This determination which was kindly made for us by Mr. W. G. Mallory gave boundaries and location of the crest in excellent agreement with our visual estimates. The form of the curve indicated, as in the case of the red band, that if complex this band must also consist of close and completely overlapping components. This band is shown graphically in Curve B of Fig. 5, in which however the relative intensities of the two bands are only approximately indicated.

To determine the strength of the two bands observations were made with the spectrophotometer; the brightness of the crests of the red and blue bands of the white and the pink kunzite under kathodo-excitation

being compared respectively with the corresponding regions in the spectrum of the acetylene flame. It was found that when the crest of the band at .690 μ in the case of the pink kunzite was made equal in brightness to the same region in the acetylene spectrum, the intensity of the crest of the blue band at .432 μ was about 43 per cent. of that of the corresponding region in the acetylene spectrum whereas the white crystal under like conditions had a blue band about 2 per cent. brighter than the acetylene spectrum. In other words when the red bands of the two varieties are equally bright the blue band of the white kunzite is about 2.33 times as intense as that of the pink variety.

ABSORPTION.

By analogy with numerous substances previously studied one would expect to find absorption bands in kunzite associated with the two fluorescence bands, of approximately the same width and displaced towards the violet. Looking through a thickness of several millimeters of the substance, however, with a hand spectroscope of small dispersion nothing of the kind is perceptible. The crystal appears to be of about the transparency of ordinary white glass and as free from selective ab-

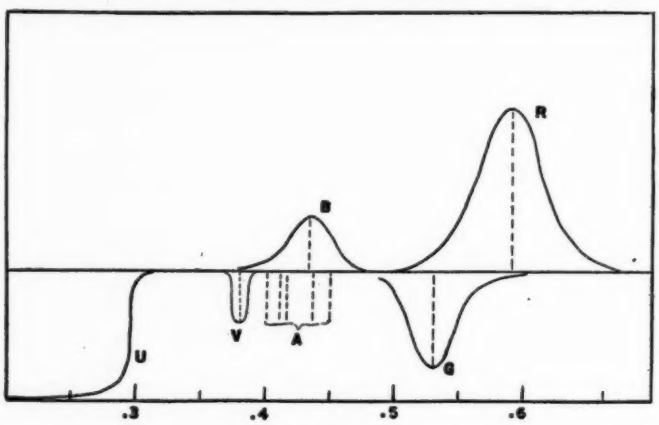

Fig. 5.

sorption. Looking lengthwise through a crystal of considerable size which afforded an absorbing layer of about 5 cm. the color of the transmitted light is distinctly purple and the spectroscope reveals a rather vague band which is by no means opaque even in the center. Spectrographs bring it out clearly but are not suitable for measurement because of the selective absorption of the film, which in all the plates at our disposal has a region of more or less pronounced weakness which overlaps this band on the side towards the violet. By spectrophotometric meas-

urements this band was easily mapped. It extends from .64 μ to .49 μ with a well-defined crest at .538 μ and, as may be seen from Curve *T*, Fig. 3, which depicts approximately the transmission of the crystal, it overlaps the violet edge of the fluorescence band *B*.

Photographs show a series of narrow absorption bands (*A*, Fig. 5) at .4019, .4117, .4170, .4375 and .4501 μ. These have a width of only about 70 Ångström units. Beyond .4 μ this thick crystal layer became rapidly opaque making the photographic exploration difficult. By placing the crystal transversely across half of the slit of a quartz spectrograph; the transmitting layer being about 4 mm., it was possible to obtain photographs extending to .3 μ, at which point even this thin layer became abruptly opaque as is indicated by Curve *U* in Fig. 5. Such photographs however failed to show the absorption bands already detected and located.

To determine if possible whether a broad band associated with the blue fluorescence existed, a series of spectrograms through crystals of such intermediate thickness as were available were made. One of these photographs, taken through a layer of 15 mm. revealed such a band lying between .3750 and .3875 μ with a crest at .380 μ. This band which lies in the usual relation to the blue band is shown at *V* (Fig. 5).

Fig. 5, to which reference has been made, is intended to depict in a rough way the fluorescence and absorption of kunzite in so far as is possible from the present study. In the diagram the fluorescence bands (*R* and *B*) are shown above the base-line and the absorption bands *A* and *V* below. Whether a group of narrow fluorescence bands associated with the group *A* exists we have not thus far been able to determine. If so they would probably be comprised within the band *B*, and unless very brilliant, would be indistinguishable.

Phosphorescence.

The phosphorescence of kunzite has certain interesting characteristics. While it is of comparatively long duration being easily discernible for several minutes after adequate excitation, decay is at first of extraordinary rapidity so that measurable brightness remains only in cases where the initial intensity of excitation is very great.

To determine the law of decay a simple photometer was improvised. It consisted of a small Lummer-Brodhun cube *L*, Fig. 6, mounted at the junction of two short tubes *C* and *D*. Light from the phosphorescent body *K* passed through a yellow screen *S* and through the central transmitting field of the cube to the eye which was focused upon the interface by means of an eyepiece of low power at *E*. The reflecting field was

illuminated by an acetylene flame with diaphragm (F) which was mounted upon a photometer bar (BB) two meters in length. The brightness of this comparison field was reduced by the interposition of a dense milk-glass screen at M and a sufficient color match was secured by means of an amber screen at Y.

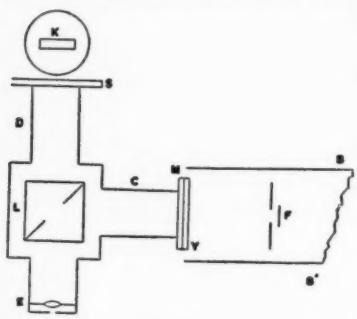

Fig. 6.

This arrangement had a range of about 180 to 1 and by substituting for the dense milk glass a ground glass at M, this could be increased to 18,000 to 1.

With the milk glass screen that part of the curve of decay from about 0.4 second after close of excitation to 60 seconds could be determined. The times of beginning and close of excitation were recorded on a chronograph and by shifting the comparison flame to successive predetermined positions on the bar and recording the times when a photometric balance was passed for each position ten or twelve points on the curve were obtained after a single excitation of the crystal.

The tube containing the kunzite crystal was connected to a Gaede mercury pump in continuous operation and under these conditions a reasonable constancy of intensity of excitation was secured.

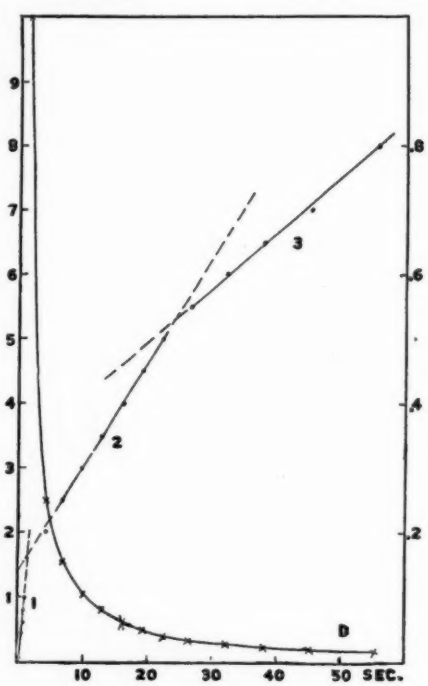

Fig. 7.

Curve D in Fig. 7 is a typical example of the numerous curves obtained with this apparatus. It shows only a small portion of the period of rapid decay immediately following the end of excitation. To include the record of the first half second of time it would be necessary to extend the ordinate of intensities about three hundred times the height of the existing diagram. Using the reciprocal of the square root of intensity as ordinates the data give the linear branches 2 and 3 in the same figure.

As is well known it has been customary to describe the decay curves of Sidot blende, willemite and numerous other substances, thus plotted, as composed of two such linear processes.[1] Lenard[2] and others have contested the linear character of the initial process although the determinations of Waggoner[3] and of Zeller[4] whose measurements covered the first few hundredths of a second, an interval impossible to observe by the usual methods, showed a linear relation between $I^{-1/2}$ and time.

In the case of kunzite the line marked "2" in the diagram clearly does not represent the initial process of the decay of phosphorescence for its intercept corresponds to an intensity far below the brightness of the substance at the close of excitation. Observations made six tenths of a second after the beginning of decay consistently gave measured intensities much greater than this intercept would indicate.

Since the excitation was by kathodo-bombardment it was easy to measure the initial brightness directly by substituting the ground glass screen and thus increasing the brightness of the comparison light one hundred times. It was also possible with this screen to determine the brightness for times ranging between 3/10 sec. and 6/10 sec.

These values plotted for $I^{-1/2}$ and time lie in a straight line which passes through the intercept for the initial brightness as measured and constitute the process marked (1) in Fig. 7. Since this process gives the true value of the intensity at the close of excitation it may be termed the initial process. It is shown on a larger scale in Fig. 8.

This result is quite in accordance with the experiments of Waggoner and of Zeller whose initial process was also linear and of a steeper slope than what had been taken for the first process in previous studies of decay of long duration.

Kunzite differs from many phosphorescent substances in its comparative inactivity to photo-excitation. A spark discharge between iron or zinc terminals sufficient to leave willemite, Sidot blende, and numerous other substances brilliantly phosphorescent has so feeble an effect on kunzite that special precautions are necessary to enable any after effect whatever to be discerned. Baskerville and Kunz[5] noticed photo-phosphorescence in the case of the white variety only and not at all in pink crystals. The latter, however, are capable of excitation as may be determined by passing a bundle of rays from the carbon arc or mercury lamp through a light

[1] Nichols and Merritt, PHYS. REV., XXV., p. 362; C. A. Pierce, PHYS. REV., XXVI., pp. 312 and 454.

[2] Lenard, Annalen der Physik, XXI., p. 641 (1910).

[3] C. W. Waggoner, PHYS. REV. (1), XXVII., p. 209.

[4] Carl Zeller, PHYS. REV. (1), XXXI., p. 367.

[5] Baskerville and Kunz, l. c.

filter transparent only to blue and the shorter waves, and then through the crystal to be examined. The ruddy path of the beam is clearly discernible particularly when viewed through an amber or yellow glass. The exciting effect of the individual lines of a mercury arc spectrum from .4359 μ to .3663 μ can also be detected with proper precautions for the exclusion of stray light.

The appearance of dichroism in the pink variety is probably due, in part at least, to its fluorescence. The disappearance of color when the crystal is viewed through a Nicol prism occurs at an angle for which the fluorescent light which as Pochettino[1] has shown is polarized, would be cut off.

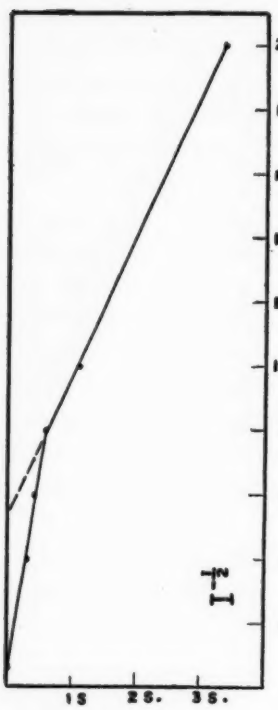

Fig. 8.

The pink color disappears, moreover, when the crystal is illuminated by rays deficient in exciting power.

May it not be that the feeble photo-excitation of kunzite, certain calcites, etc., is due to their transparency even in the absorption band? Kunzite is almost impervious to X-rays and responds to their excitation while the kathode rays, which are completely absorbed, produce the most powerful effect.

Like most, if not all, substances whose phosphorescence is of long duration, kunzite requires an appreciable time to reach its maximum of excitation. Under kathodo-bombardment saturation is reached after a few seconds. The length of time required for the phosphorescence to decrease to 1/18,000 of the initial brightness was no greater after an excitation of five minutes than after ten seconds. Excitation of less than one second however produced phosphorescence of comparatively short duration, the time of decay to 1/18,000 being about one half that for the longer exposures. Under the feebler excitation by X-rays or when the sparks from a Holtz machine are caused to pass across the surface of the crystal it is possible to follow with the eye the gradual growth of the fluorescence.

We did not attempt to make a quantitative study of these phenomena because kunzite suffers fatigue under continued bombardment from which its complete recovery is slow. Indeed there is undoubtedly a permanent

[1] Pochettino, l. c.

effect which shows itself, as in many other substances, in a dullness and discoloration of the surface. Red and infra-red rays have no appreciable effect upon the degree of excitation or the rate of decay. In this respect kunzite differs from Sidot blende.

In all the measurements on phosphorescence the substance was viewed through a yellow screen (*S*, Fig. 6) in order to prevent blending of the light from the two bands. This was however an unnecessary precaution since the blue band is of exceedingly rapid decay as could easily be determined by observation through a blue screen. No after effect lasting as much as a tenth of a second could be detected.

In this respect kunzite is similar to the phosphorescent sulphides of Lenard and Klatt and it resembles them also in becoming inactive, according to Pochettino, at about 400°.

Throughout these experiments the important feature of polarization was ignored. That a detailed study of this aspect of the luminescence of kunzite would yield interesting results there is little doubt. Indeed the general subject of the polarization phenomena in luminescence, concerning which we have as yet only the suggestive data of Pochettino, J. Becquerel and a few other observers deserves further consideration.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY,
April 18, 1914.

NOTE ON THE RELATION BETWEEN THE EMISSION SPECTRUM OF A COMPOUND AND ITS ABSORPTION SPECTRUM IN SOLUTION.

BY ALBERT K. CHAPMAN.

IT is the intention of this note to call attention to a certain relation which appears to exist between the spectrum of a compound, excited by the ordinary vacuum tube discharge, and the absorption band which the same compound exhibits when in solution. In every case the compound was introduced into a spectrum tube of the usual form, fitted with aluminum electrodes, exhausted, sealed off and excited by the discharge from an induction coil. The tube was heated in order to vaporize the compound; the compounds used having been selected simply on account of their low melting points.

In the case of mercuric iodide the pressure was reduced to about 0.08 mm. when sealed off. Before heating, when the discharge was allowed to pass, the spectrum showed the lines of mercury and iodine, beside those due to the residual air. After the tube had been sufficiently heated to vaporize the mercuric iodide to a considerable extent, the character of the discharge was radically changed, becoming an intense violet in color. In addition to the lines of mercury and iodine there appeared a brilliant band, shading off toward both the red and the violet, extending from about λ 4420 to λ 4450 as seen visually: on the photographic plate it is shown broader. All measurements were taken by means of a Hilger constant deviation spectrometer. For making the photographs the telescope was replaced by the usual camera of 21-inch focal length. In observing the absorption spectrum the following solution was used:

KI	11.18 gr.
HgI_2	10.60 gr.
Water	100.0 gr.
Thickness of absorbing layer	12.32 cm.

The observations were made at room temperature with a Nernst glower as the source of continuous spectrum. It was necessary to use the potassium iodide in order to get the mercuric iodide into solution: a separate solution of potassium iodide was examined for absorption but none was found.

Fig. 1 shows: (*a*) Continuous spectrum of Nernst glower. (*b*) Absorption spectrum of mercuric iodide solution. (*c*) Mercuric iodide spectrum. (*d*) Mercuric iodide spectrum (shorter exposure). (*e*) Iodine spectrum. (*f*) Mercury arc spectrum. (*g*) Oxygen spectrum.

It will be observed that the emission and absorption bands correspond, although it is to be remembered, of course, that the width of the absorption band may be changed by varying the concentration, thickness of absorbing layer, etc. As no photographic scale was available for comparison, a few of the prominent lines are marked.

A similar set of observations was made on stannic iodide, the tube having been exhausted to 0.07 mm. In this case it was not necessary to heat the tube as it became hot enough from the discharge to vaporize the compound. In addition to the lines for tin, iodine, oxygen and nitrogen, the spectrum showed a band extending from about λ 5160 to the violet limit of visibility. The following is the absorption solution used:

SnI_4	0.1790 gr.
Ethyl alcohol	100 c.c.
Thickness of absorbing layer	1.95 cm.

Fig. 2 is as follows: (*a*) Continuous spectrum. (*b*) Absorption spectrum of solution. (*c*) SnI_4 in vacuum tube, 25 min. exposure. (*d*) SnI_4 in vacuum tube, 15 min. exposure. (*e*) SnI_4 in vacuum tube, 7 min. exposure. (*f*) Tin spark with capacity. (*g*) Iodine spectrum. (*h*) Oxygen spectrum.

The absorption covers the region from the extreme violet to about λ 5330, while the emission band extends from the violet to λ 5160, giving fair agreement between the emission and absorption bands.

In the case of ferrous iodide the spectrum was very faint and difficult to photograph; pressure 0.01 mm.

SOLUTION.

FeI_2	1.075 gr.
Sugar	10.00 gr.
Water	600 c.c.
Thickness of absorbing layer	1.93 cm.

Fig. 3 is as follows: (*a*) Continuous spectrum. (*b*) Absorption spectrum of solution. (*c*) FeI in vacuum tube. Here again the emission band corresponds to the absorption band but does not extend so far into the violet. The main emission band extends from about λ 4550 to λ 4850, but there is also a faint emission band at λ 4150. Longer exposure might have shown this to be wider.

It is interesting to note, in this connection, that mercurous chloride

gives a very strong emission band from λ 5350 to λ 5750, while the salt itself is white and insoluble except in very small quantities. The emission spectrum is shown in Fig. 4.

It is seen that a wide emission band, shading off toward both the violet and red, is characteristic of the compounds investigated. When the absorption spectrum of the compound is available, there seems to be a definite relation existing between the absorption and emission bands. It would seem, therefore, that the vibrating system responsible for the emission is also effective in producing absorption in solution.

These experiments were carried on at the Physical Laboratory of the Ohio State University under the direction of Dr. A. W. Smith, to whom my thanks are due for his help and interest at all times.

PALMER PHYSICAL LABORATORY,
PRINCETON UNIVERSITY.

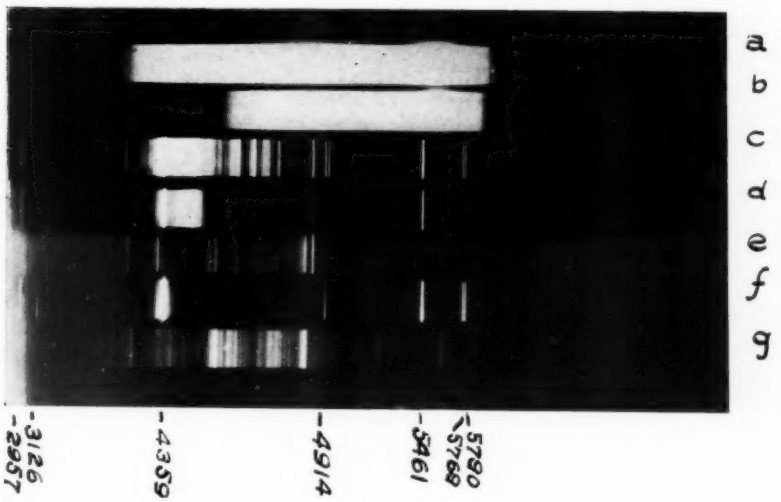

Fig. 1.

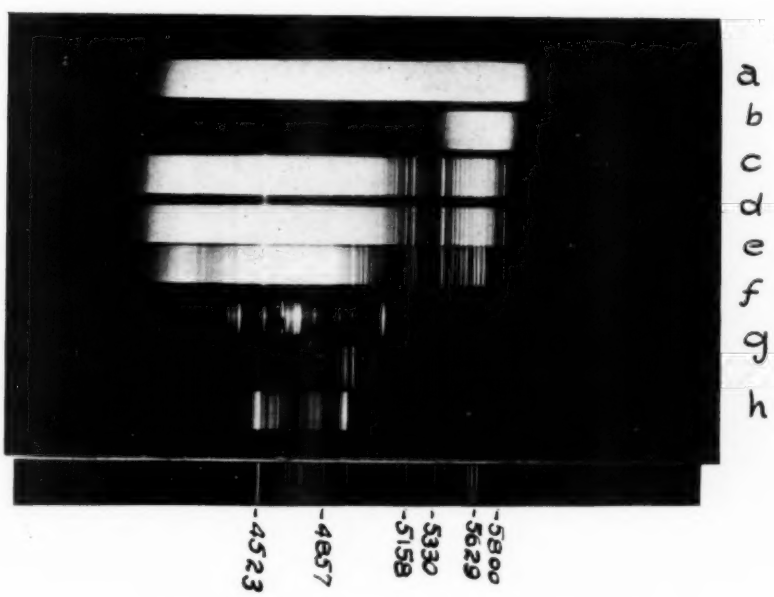

Fig. 2.

ALBERT K. CHAPMAN.

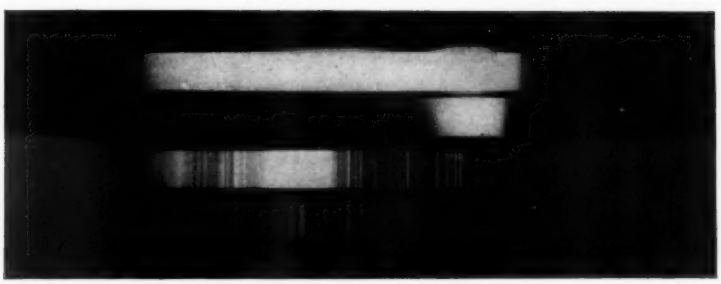

Fig. 3.

Fig. 4.

ALBERT K. CHAPMAN.

SOME BRUSH DISCHARGE PHENOMENA PRODUCED BY CONTINUOUS POTENTIALS.

By Stanley P. Farwell.

Introduction.

When there exists a large difference of potential between a wire and neighboring conductors such as a similar and parallel wire, or a coaxial cylinder, the discharge phenomenon known as corona is likely to occur. For alternating differences of potential, this phenomenon has been extensively studied by Peek, Whitehead, Russell and others. The alternating corona takes the form of a more or less continuous and uniform bluish glow along the wire. The corona produced by continuous potentials has not received so much attention, presumably on account of the fact that its practical bearing on engineering problems is not so great. Watson[1] and Schaffers[2] have carried out experiments on the corona thus produced. Watson has experimented on wires as small as 0.7 mm. and at pressures as low as 360 mm. Schaffers has worked with cylindrical fields, using wires as fine as 0.006 mm. and various sizes of tube and has determined the critical voltage for visual corona at atmospheric pressure.

Description of Experiments.

The writer has been studying the corona as produced by continuous potentials for wires from 0.037 mm. to 1.285 mm. diameter and tubes 3.50 cm. and 4.45 cm. diameter. The relation between difference of potential and current between wire and tube has been studied for atmospheric pressure for the different sizes of wire; the critical voltage for visual corona has been obtained for pressures from somewhat above atmospheric down to 2.0 mm. of mercury and the character of the discharge noted; and the effect of variation of voltage for a constant low pressure has been investigated.

The object of this paper is to present especially some of the phenomena observed at these lower pressures, the influence of a short arc in series with the apparatus upon the character of the discharge, and the increase of pressure in the tube due to the ionization.

[1] Watson, Electrician, Sept. 3, 1909, Feb. 11, 1910, Feb. 18, 1910.

[2] Schaffers, Comptes Rendus, July, 1913, p. 203.

INFLUENCE OF PRESSURE UPON CHARACTER OF DISCHARGE.

The series of photographs in Fig. 1 represents the change in the discharge when the wire is negative to the tube and the pressure in the tube is varied from a low value up to atmospheric. The wire was No. 30 B. & S. (0.26 mm. diameter) bare copper taken from a coil obtained from the manufacturer. A glass tube 25 cm. long was lined with a brass sheath, except for a slit 6 mm. wide extending from end to end, and having an internal diameter of 3.5 cm. The wire was stretched tightly along the axis, passing through glass plates at the ends. The tube was rendered air tight by sealing wax and it could be exhausted through a branch tube attached to the side of the cylinder.

For the lowest pressures, the discharge takes the form of brilliant beads encircling the wire. Each has a bright cylindrical core, outside of which is a dark space which in turn is surrounded by a purplish glow extending out for some distance from the wire. As the pressure is increased, the difference of potential required to produce a discharge increases, and the number of beads increases. The central nucleus contracts and the bead becomes more and more like a brush until finally there is a line of brushes along the wire. Each brush consists of a bright spot on one side of the wire, with a fan-like purple glow spreading out from it, the plane of the fan being perpendicular to the axis. With the slit tube, the brushes point in different directions but if a similar test be run on a tube without a slit and one looks along the wire, the bright nuclei are seen to lie all in a plane, with alternate brushes on opposite sides of the wire, as a general rule.

As the pressure is raised toward atmospheric the isolated brush type of discharge gives place to such a discharge as is pictured in Fig. 1 for 357.0 mm. pressure. An occasional brush is left, mixed up with a more or less continuous glow which is very irregular. For atmospheric pressure, the discharge looks like the upper picture. The isolated brushes are very few, the rest of the wire presents an extremely "messy" appearance, the glow is bright and purplish and the discharge seems in constant movement.

For the lower pressures, a slight increase of voltage above that required to produce beads is sufficient to produce a violet arc-like discharge across the gap between wire and tube at one or two points and if this discharge be allowed to continue, the wire will be burned in two.

The photographs for 261.8 mm. pressure in Fig. 2 show the transition from one form of discharge to another, as it takes place for somewhat higher pressures. At the critical voltage, a continuous glow appears. Then as the voltage is raised slightly, the glow becomes spotted, followed,

at a higher voltage, by the gradual breaking up of the glow into the isolated brush form of discharge. Sometimes this process is not so gradual as here indicated. Suppose a difference of potential be impressed of a value above that required to just produce a glow. At the instant of closing the circuit, one sees a continuous glow which dissolves into the brush discharge, the brushes emerging one by one, until the entire wire is strung with them. The upper picture illustrates the regularity of spacing of the brushes, which will be taken up later.

The characteristic appearance of the discharge with the wire positive is that of continuous, uniform, bluish glow of diameter little greater than that of the wire. Its appearance is not noticeably changed by changes in pressure, but it gets brighter with increasing difference of potential.

EFFECT UPON DISCHARGE OF AN ARC IN SERIES.

The effect upon the discharge of a short arc in series with the apparatus is shown in Fig. 2 for a pressure of 112.6 mm. When the wire is positive, the introduction of an arc causes the glow to brighten, increase in diameter, become more purple, and more ill defined as to boundary. The currents recorded on the photographs are obtained from the deflections of a D'Arsonval galvanometer. When the arc is introduced, the current so obtained is much less than one would expect from the small increase in resistance of the circuit caused by the arc. Evidently the discharge with arc in series is made up of two forms of discharge superimposed; the effect due to the continuous potential and an alternating effect caused by the oscillations set up in the circuit by the arc.

This superposition of effects is clearly illustrated when the wire is negative. The arc here causes a marked change in the discharge. The result is a continuous glow with a few isolated brushes strewn along it.

To test out the effect produced by the arc in apparently producing oscillations in the circuit, a condenser was connected across the cylindrical field. The introduction of the condenser caused the discharge to take the same form it had before the arc was introduced, except for there being a few less brushes. When there is a condenser thus in the circuit and the switch is closed, the transition from a continuous negative glow to the brush form of discharge is prolonged. With the condenser still in the circuit, the disconnection of the impressed difference of potential gives an opportunity for a discharge of the condenser across the cylindrical field. At the instant the line circuit is opened, no change in the appearance of the brushes is noticeable. Then as the condenser discharges and its potential falls, there is presented a "moving picture" of the stages of the discharge down to darkness. This discharge was a matter of several

seconds. As the voltage fell, the brush type of discharge was maintained: each regular arrangement of brushes giving place to another regular arrangement of fewer brushes. Since the resistance of the field is large, the condenser discharge must be of the continuous type.

DISCHARGE BETWEEN PARALLEL WIRES.

Two No. 34 copper wires were placed parallel and 2 cm. apart inside a tube of glass 25 cm. long and the photographs of Fig. 3 were taken for pressures less than atmospheric. The tendency of the negative wire to show an isolated brush discharge and the positive to give a continuous glow is evident here. There is evidently a tendency for the positive sections of continuous glow to break up into spots or streamers. For constant pressure, the increase of the number of sections of the discharge with increase of voltage will be noted. The spacing of the sections is approximately regular and would undoubtedly be more so if the wires were more exactly parallel and stretched more tightly to make them straighter.

The two upper photographs show the effect produced by an arc in series. There is no longer the great difference between the appearance of the two wires. The negative wire, however, still shows a tendency to discontinuity of discharge. When the current is sufficiently great, violet streamers cross between the wires as shown in the upper picture. The current indicated is, again, only the component given by the galvanometer.

SPACING OF BRUSHES AS A FUNCTION OF THE VOLTAGE.

The slit tube previously described was fitted with an arrangement for stretching the wire tighter and a series of photographs was taken of the discharge under constant pressure, with the wire negative and varying difference of potential. This series is shown in Fig. 4. The lowest picture shows the appearance of the discharge at a voltage little higher than that required to produce visual corona. It will be noticed that there are many tiny brushes and no regularity of spacing. For a little higher voltage, the number of small brushes has decreased and there are a number of large brushes disposed at quite regular intervals. The succeeding photographs show the effect of increasing the voltage still further. The number of brushes continually increases and the spacing is very regular. For the lower voltages, the brushes are fixed in position for a given voltage and will always show up in the same position as the circuit is interrupted and then closed again. When the voltage approaches the value at which there will be an arc between wire and tube, each brush is in constant movement back and forth in a short path, but the number of brushes is constant for a given voltage.

Fig. 5 shows the relation between difference of potential and current. In connection with this graph it might be noted that the critical voltage for visual corona was 2,440.

It would appear from a close observation of the character and spacing of the brushes that there are only certain voltages for which there appears a regular distribution of full-sized brushes. For intermediate voltages,

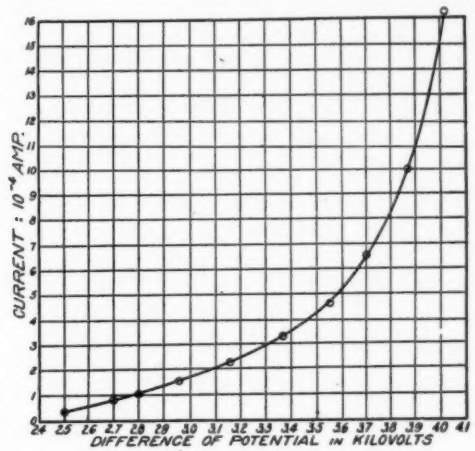

Fig. 5.

there is more or less irregularity in the size of the brushes and their spacing. For the pictures of Fig. 4 an effort was made to pick out those points at which the distribution was the most regular. Fig. 6 shows the vari-

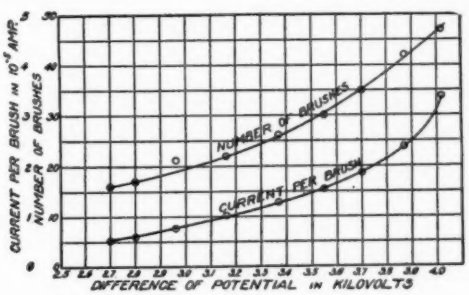
CURRENT PER BRUSH IN 10^{-4} AMP.
NUMBER OF BRUSHES
NUMBER OF BRUSHES
CURRENT PER BRUSH
DIFFERENCE OF POTENTIAL IN KILOVOLTS

Fig. 6.

ation with the difference of potential of the number of full-sized brushes and the current per brush. When there was a marked variation in the size of the brushes an estimate was made of the equivalent number of full-sized brushes. These graphs clearly indicate that a definite relation exists between the voltage and the number of brushes, for a given pressure, and that the current per brush is not a constant but also varies with the voltage.

The question may be raised as to whether the isolated brush form of discharge may not be due to oscillations in the circuit. In order to make it clear that this is essentially a direct current phenomenon, there is given below a description of the generating apparatus used in producing the continuous potentials and some experiments and arguments which support this view.

The source of electromotive force was a battery of small direct-current generators, self-excited and connected in series. The machines were rated at 500 volts and 250 watts and there were thirty in all, giving 15,000 volts at normal voltage. The machines were arranged in two sets, ten in one and twenty in the other, each set being driven by its own direct current motor. Variation of voltage was obtained by field control of the generators and of one of the motors. To prevent damage to the machines through short-circuits, a water resistance of a rather large value was connected between the generating apparatus and the tube. The negative terminal of the machines was grounded. Electrostatic voltmeters were used to measure the difference of potential and a D'Arsonval galvanometer in connection with an Ayrton shunt box to give the current.

The appearance of the brushes and the current indicated by the galvanometer are constant for a given voltage, no matter what combination of machines are used as the source of potential. One of the sets may be used and the appearance of the spots and the voltage and current noted. Then if the other set be used to give the same voltage with a different number and speed of machines, the same results are obtained. If there were oscillations set up perhaps by sparking at the brushes, we would not expect this agreement.

Mention has been made before of the effect of the introduction of a condenser in parallel with the tube. To test whether the current sent through the tube by the condenser in discharging was direct or oscillatory, another experiment was performed. The condenser was connected across the positive and negative bus-bars to which the generating apparatus was connected through the water resistance. Then a switch connecting the machines to the bus-bars was closed as was also a switch leading to the tube. The deflection of the galvanometer was noted and the appearance of the brushes. Then the generator switch was opened and the condenser discharged through the tube and the galvanometer. After the switch was opened, the galvanometer deflection gradually decreased, the rate of decrease of the deflection being slower and slower as the discharge proceeded. The opening of the switch caused no immediate change in the brushes, only the gradual change already noted.

That the discharge of the condenser must be continuous is shown by the deflection of the galvanometer and it can be further proved by a rough calculation. Assuming the resistance of the cylindrical field as given by E/I and taking a set of values of E and I for the comparatively low pressures at which the brushes are best formed, we obtain $R = 1.83 \times 10$ ohms. Assuming the very large value of 0.1 henry for the inductance of the circuit, and the approximate value of 2 mf. for the capacity, we find the R is about 4.1×10^4 times as great as $\sqrt{4L/C}$ and hence it is clear that the condenser discharge must be of the continuous type.

By running wires from the terminals of an induction coil to the central wire and the tube and then adjusting the discharge points on the coil to such a distance that a silent discharge took place between them, it was possible to obtain an almost uniform hazy glow along the wire. But no effect could be obtained like the uniformly spaced brush discharge.

It is well known that an arc is the source of electrical oscillations and it has been shown by a previous figure that a short arc in series with the tube disturbs the brushes due to the direct current by the superposition of an alternating current effect so that the glow becomes more or less uniform and the difference in the appearance of the glow for different polarities becomes much less. So the introduction of an oscillatory current acts to suppress the isolated brush form of discharge and not to cause it.

The difference between positive and negative electricity is hardly better demonstrated by any other phenomenon. It should be stated here, however, that Peek[1] by a stroboscopic method has also observed "more or less evenly spaced beads" on the negative wire when there was corona between parallel wires caused by an alternating difference of potential of 80,000 volts at atmospheric pressure. The wires used by Peek were 0.168 cm. in diameter, spaced 12.7 cm. apart.

Effect of Magnetic Field.

A strong horseshoe electromagnet was placed in various positions with its poles against the tube and the effect upon the various forms of discharge of making and breaking the magnet circuit was observed. No change could be noted in the appearance of the discharge or the current flowing.

Variation of Pressure in Tube with Voltage.

A No. 36 B. & S. copper wire, 0.135 mm. in diameter, was stretched tightly along the axis of a brass tube 4.45 cm. in diameter and closed at

[1] Proc. A. I. E. E., Vol. 31, No. 6, p. 1123 and Plate LXV.

the ends by glass plates through which the wire passed. A small branch tube was soldered to the side of the main tube and from it connection was made to an air-pump. An open manometer of small bore containing a light oil was connected to the side of the branch tube. Everything was rendered airtight after disconnecting the manometer and the tube was exhausted. Then dry air was gradually admitted through a tube containing soda-lime and a wash-bottle containing concentrated sulfuric acid, until the pressure was again atmospheric, 744.0 mm. in this case. The manometer was again connected and various differences of potential impressed.

As soon as the voltage reached the critical value to cause an appreciable current to flow, a jump in the columns of the manometer was apparent. This jump occurred lower for the wire negative and it was difficult to tell just the voltage at which it began. When the wire is negative, any little dust particle on it will be sufficient to start a discharge at a lower voltage than would be required to cause a general glow along the whole wire. But for the wire positive, the critical point is very marked and the jump occurs, as closely as one can judge, at the same time that a faint bluish glow is seen along the wire. Fig. 7 shows the increase in the

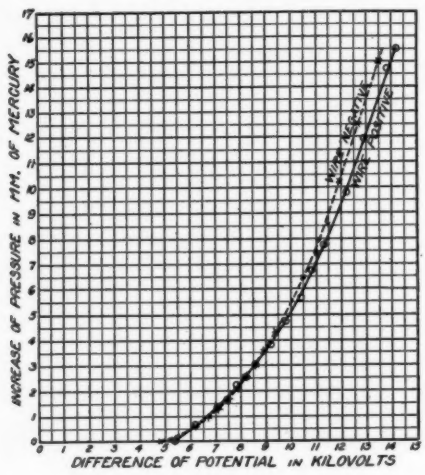

Fig. 7.

pressure as the voltage is raised. This graph has exactly the same appearance as the graph plotted between voltage and current, as one might expect from the theory of the conduction of electricity through gases. It will be noted how the curves for the two polarities cross at low voltages and that the increase of pressure for a given voltage is greatest for negative

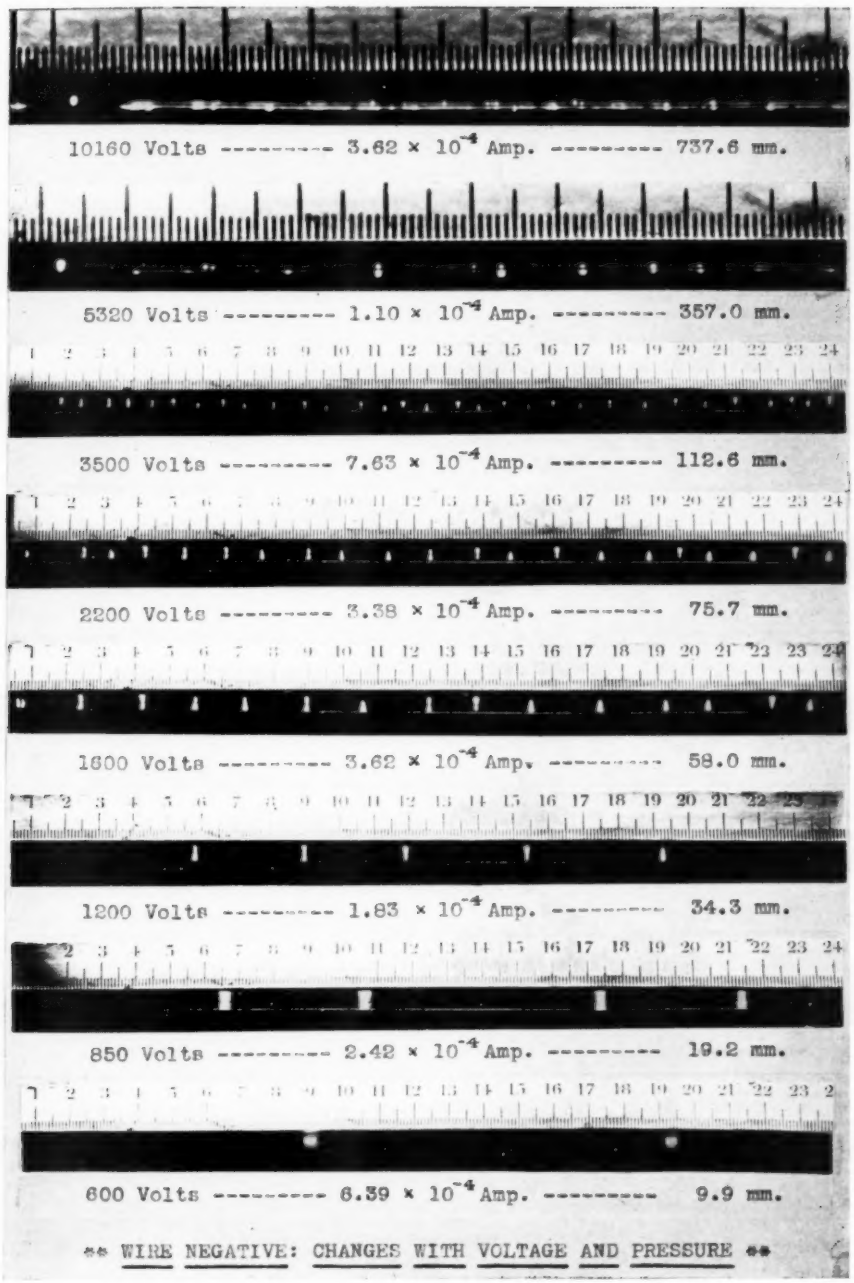
10160 Volts --------- 3.62 × 10⁻⁴ Amp. --------- 737.6 mm.
5320 Volts --------- 1.10 × 10⁻⁴ Amp. --------- 357.0 mm.
3500 Volts --------- 7.63 × 10⁻⁴ Amp. --------- 112.6 mm.
2200 Volts --------- 3.38 × 10⁻⁴ Amp. --------- 75.7 mm.
1600 Volts --------- 3.62 × 10⁻⁴ Amp. --------- 58.0 mm.
1200 Volts --------- 1.83 × 10⁻⁴ Amp. --------- 34.3 mm.
850 Volts --------- 2.42 × 10⁻⁴ Amp. --------- 19.2 mm.
600 Volts --------- 6.39 × 10⁻⁴ Amp. --------- 9.9 mm.
** WIRE NEGATIVE: CHANGES WITH VOLTAGE AND PRESSURE **

Fig. 1.

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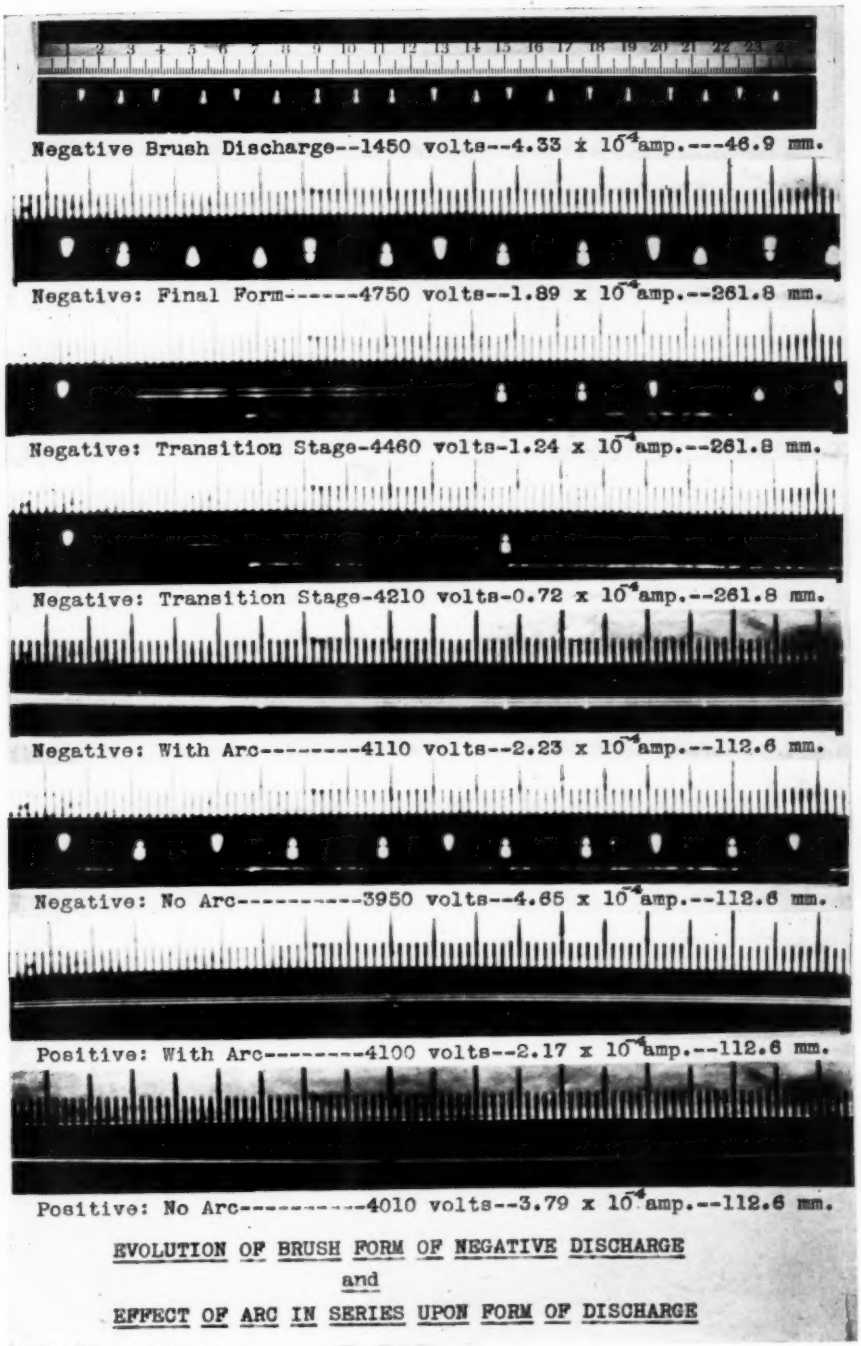
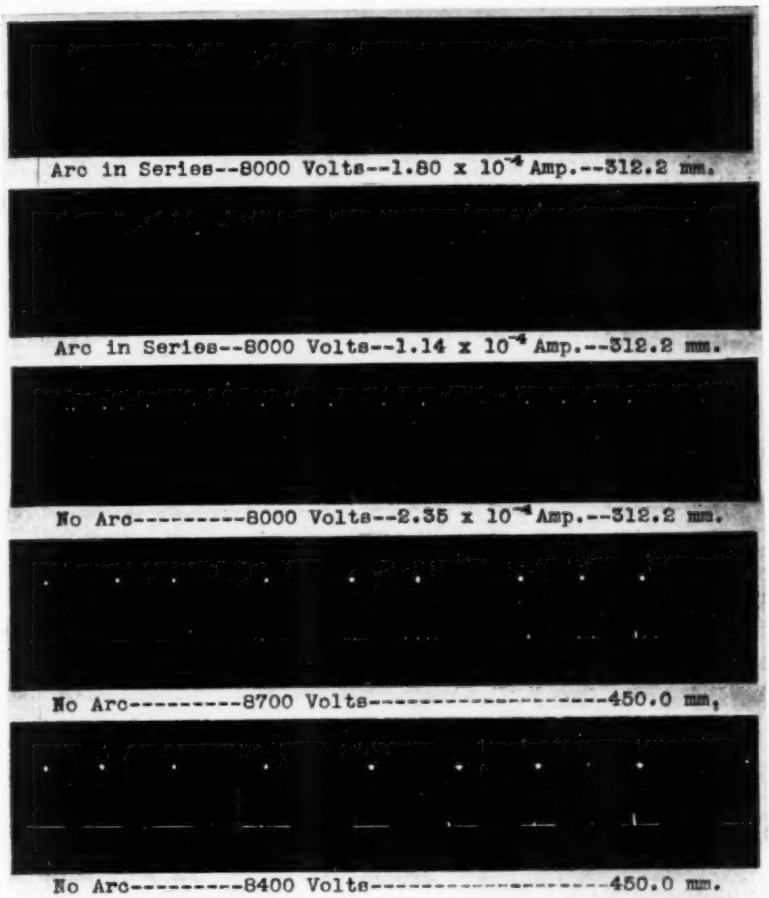

Negative Brush Discharge--1450 volts--4.33 x 10⁻⁴amp.---46.9 mm.
Negative: Final Form------4750 volts--1.89 x 10⁻⁴amp.--261.8 mm.
Negative: Transition Stage-4460 volts-1.24 x 10⁻⁴amp.--261.8 mm.
Negative: Transition Stage-4210 volts-0.72 x 10⁻⁴amp.--261.8 mm.
Negative: With Arc--------4110 volts--2.23 x 10⁻⁴amp.--112.6 mm.
Negative: No Arc----------3950 volts--4.65 x 10⁻⁴amp.--112.6 mm.
Positive: With Arc--------4100 volts--2.17 x 10⁻⁴amp.--112.6 mm.
Positive: No Arc----------4010 volts--3.79 x 10⁻⁴amp.--112.6 mm.
EVOLUTION OF BRUSH FORM OF NEGATIVE DISCHARGE
and
EFFECT OF ARC IN SERIES UPON FORM OF DISCHARGE

Fig. 2.

STANLEY P. FARWELL.


Arc in Series--8000 Volts--1.80 x 10⁻⁴ Amp.--312.2 mm.
Arc in Series--8000 Volts--1.14 x 10⁻⁴ Amp.--312.2 mm.
No Arc---------8000 Volts--2.35 x 10⁻⁴ Amp.--312.2 mm.
No Arc---------8700 Volts----------450.0 mm.
No Arc---------8400 Volts----------450.0 mm.

SOME FORMS OF DISCHARGE BETWEEN PARALLEL WIRES

#34 Wires-0.165 mm.-2 cm. apart-25 cm. long
Upper Wire is Negative

Fig. 3.

STANLEY P. FARWELL.

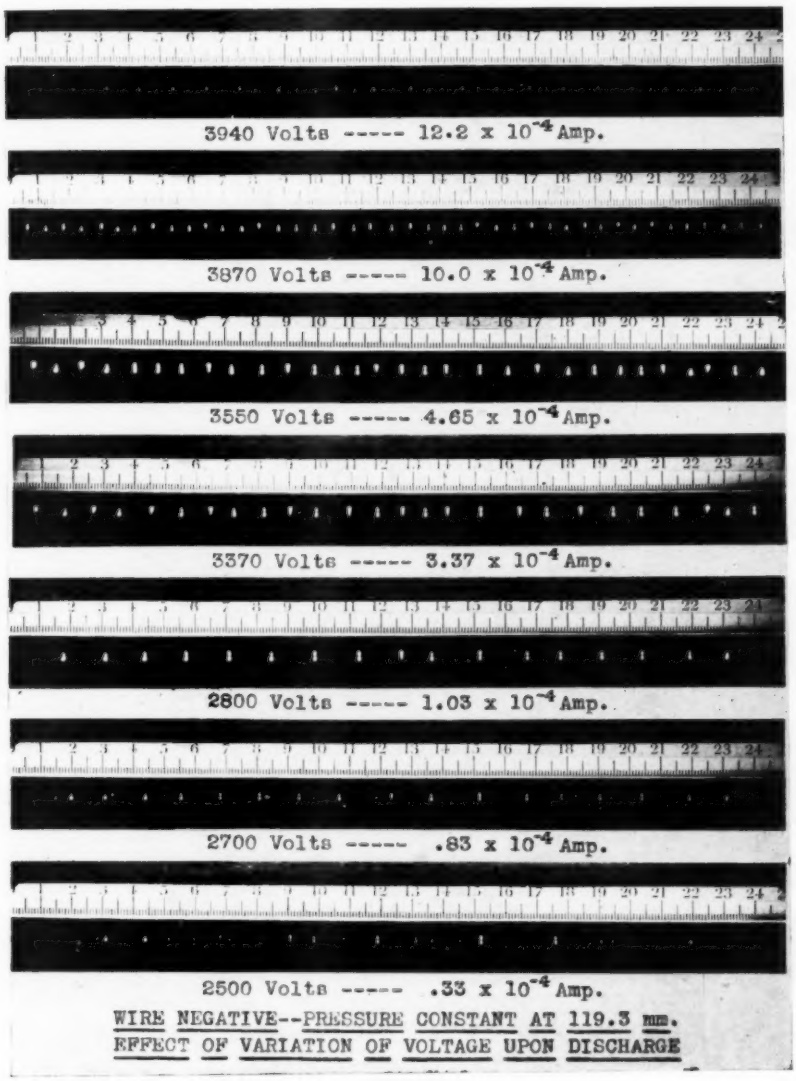

3940 Volts ----- 12.2 x 10^{-4} Amp.
3870 Volts ----- 10.0 x 10^{-4} Amp.
3550 Volts ----- 4.65 x 10^{-4} Amp.
3370 Volts ----- 3.37 x 10^{-4} Amp.
2800 Volts ----- 1.03 x 10^{-4} Amp.
2700 Volts ----- .83 x 10^{-4} Amp.
2500 Volts ----- .33 x 10^{-4} Amp.
WIRE NEGATIVE--PRESSURE CONSTANT AT 119.3 mm.
EFFECT OF VARIATION OF VOLTAGE UPON DISCHARGE

Fig. 4.

STANLEY P. FARWELL.

polarity of the wire during the greater part of the range. The crossing of the curves is typical of the voltage-current graphs.

In addition to the sudden jump at closure of the circuit there is a gradual increase of pressure due to the heating effect of the current and hence care was taken to read the heights of the columns of liquid as soon as possible after the circuit was closed.

The work upon which this paper is based was performed in the laboratory of physics at the University of Illinois under the direction of Dr. Jacob Kunz, asst. prof. of physics. To him and to Prof. E. B. Paine, of the electrical engineering department, the writer wishes to acknowledge his indebtedness for many helpful suggestions as to the conduct of this work.

Laboratory of Physics,
University of Illinois,
April, 1914.

THE REPRODUCTION AND MEASUREMENT OF VERY SHORT INTERVALS OF TIME.

BY JOHN COULSON.

IT is often found desirable to have at one's disposal some means by which two neighboring electric circuits can be broken in quick succession in such a way that the interval between these two operations is accurately predictable and under the control of the experimenter. This paper contains a brief description of a simple apparatus which can be made to give time intervals of very short duration.

This work was suggested to the writer by Professor B. O. Peirce, to whom it was of much interest, since he required in his investigation of the dielectric constants of certain materials, a shorter time interval than was attainable, with accuracy, by any known apparatus. The many devices then in use either gave intervals much longer than would serve, or intervals which could not be repeated with a sufficient degree of accuracy.

The measurement of very short intervals of time is a matter of but little difficulty. More than sixty years ago Helmholtz[1] used in his investigation "*Sur la vitesse de propagation de l'agent nerveux dans les nerfs rachidiens*," a horizontal magnetic pendulum for determining the duration of an electric impulse. The apparatus was of the form of a Thompson galvanometer, and the angular deviation of the magnet from its position of rest was taken as a measure of the duration of the electric impulse sent through the galvanometer. The behavior of such swinging magnets had been studied by Gauss and W. Weber[2] while making their magnetic measurements at Göttingen.

Of the many methods used by later investigators for measuring such intervals, perhaps the best is by determining either the partial discharge from a loaded condenser,[3] when short-circuited during the interval in question through a given non-inductive resistance, or the fractional part

[1] Helmholtz, Comptes Rendus, 30, 1850; 33, 1851.

[2] Gauss, and W. Weber, Resultaté des Magnetischen Vereins, 1837.

[3] H. R. Kempe, Handbook of Electrical Testing, 1887, 4th ed.; Mascart and Joubert, Electricity and Magnetism, 1888, Vol. 2; Devaux-Charbonnel, Comptes Rendus, 142, 1906; L'Electricien, 31, 1906; H. W. Morse, and C. L. B. Shuddemagen, Proc. Am. Acad., 44, 1908; C. L. B. Shuddemagen, Proc. Am. Acad., 44, 1908.

of a full charge acquired by an originally empty condenser through a given non-inductive resistance when a constant-electromotive force was applied throughout the charging time interval. It has long been known that by a proper choice of apparatus this method of procedure yields very accurate measurements, and is capable of being applied in a variety of ways. It furnishes a satisfactory means of determining the time of contact of a hammer and an anvil,[1] or the velocity of a projectile, or the "specific duration"[2] of impinging spheres. For many years Professor Peirce had as regular experiments in his course on experimental electricity and magnetism, the determination of cable insulation resistance, and the time of contact of two impinging steel balls, as applications of this method. He also applied it in his investigation on the duration of a "quick tap on a telegraph key."[3] In every case, when the apparatus was properly set up, this method has proven to be a good one, yielding results which are limited in accuracy only by the unsteadiness of the ballistic galvanometer used to measure the condenser charge.

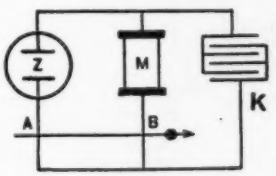


Fig. 1.

Apparatus arranged for the determination of the unloading time.

The problem of finding the fractional part of a full charge left on a condenser after unloading through a non-inductive resistance for an interval of t seconds is a simple one, and the solution is very familiar. Let the apparatus be arranged in some such form as indicated in Fig. 1, where Z is a battery of constant-electromotive force, M a variable non-inductive resistance, and K a standard condenser. Suppose the condenser has acquired its full load Q_0; then, if the battery lead be severed at A by a rifle ball, the condenser will discharge through the resistance r, made up of M and the lead wires, until the ball cuts the second wire at B; and the charge left on the condenser will be, $Q_t = Q_0 e^{-t/kr}$ where t is the time taken by the bullet to travel from A to B, and k the capacity of the condenser in farads. If t is the quantity sought, as in the present investigation,

$$t = kr \log_e \frac{Q_0}{Q_t}.$$

With the aid of a suitable ballistic galvanometer and key, both Q_0 and Q_t can be easily determined.

The design of an apparatus which will repeatedly give the same ex-

[1] R. Sabine, Telegraphic Journal, 4, 1876; Phil. Mag., 1, 1876.

[2] A. E. Kennelly, and E. F. Northrup, Journal of the Franklin Institute, 1911.

[3] B. O. Pierce, Proc. Am. Acad., 42, 1908.

tremely short interval of time within say one per cent. of itself, so that it can be controlled and used without measuring its duration in every experiment, is a matter of much greater difficulty. It has been customary to use a bullet travelling at a high velocity to sever two parallel lines placed close together, but the results from successive observations by this method often differ as much as 25 per cent. Fig. 2 is reproduced from the photograph of a bullet which was in the act of severing two wires while travelling at a velocity of 500 meters per second. The photograph was taken by Mr. W. A. Hyde, Bureau of Ordnance, Navy Department, to whom I am indebted for permitting its reproduction. It illustrates what has long been known, that even the most brittle material, placed in the path of a bullet under high velocity, will bend before it breaks, and very often drag on the sides of the bullet; which in either case may cause serious errors.

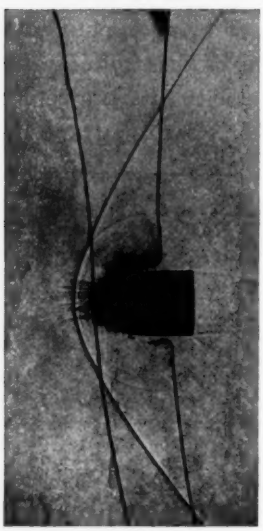


Fig. 2.

Bullet, travelling with a velocity of 500 meters per second, in the act of breaking two parallel wires placed in its path. It is evident that the ruptured wire bent very perceptibly before breaking.

The apparatus here described is based on a different principle. If a massive weight, falling freely under gravity, strikes a collar on a metal rod which is supported vertically, an elastic wave or impulse travels out along the rod in each direction from the collar with a finite velocity.[1] It is evident that if the impact takes place at the middle point of the rod, these waves will reach the ends of the rod at the same time. If, however, the point at which the impact occurs be not at the middle of the rod, the impulses thus started will reach the ends at times that differ by an interval which will depend on the path differences. In this way controllable time intervals extending over a considerable range may be secured, and can be measured easily with the aid of proper apparatus. I have experimented with numerous forms in order to be sure that the elastic wave excited in the comparatively long stout metal rods used was of sufficient magnitude to interrupt the passage of current in two related circuits, of which the rod in question formed a part, by breaking contacts at its extremities.

Fig. 3 shows diagrammatically the arrangement of the apparatus which has given the most consistent results. The framework, about 2 meters

[1] A. E. H. Love, Mathematical Theory of Elasticity, 2d ed., 1906.

in height, and 40 centimeters wide, constructed from well seasoned pine studs 5 centimeters thick, and 15 centimeters wide, stands on a concrete foundation, and is bolted to the brick wall of the laboratory thus avoiding all possible jarring of the apparatus when in use. The central crosspiece, which is subjected to heavy blows when the apparatus is in operation, consists of a heavy block of oak set into the sides of the frame, and held fast by long screws. The rod *AB*, which serves as a circuit breaker is of Bessemer steel 1.3 centimeters in diameter, it terminates in a square metal block

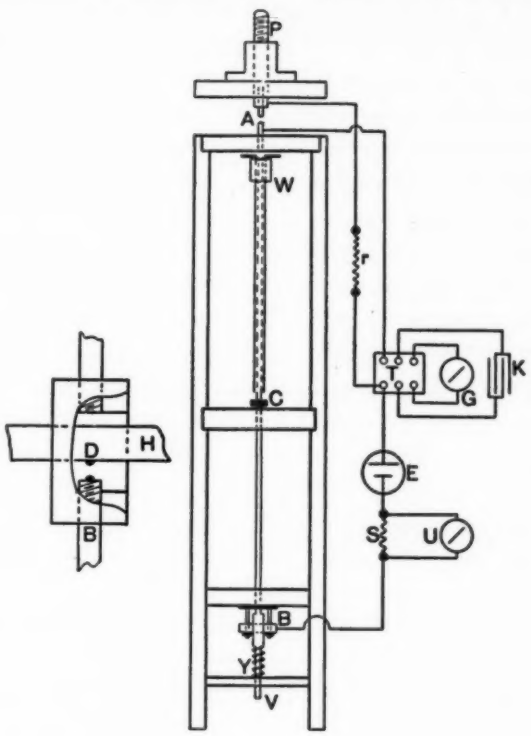


Fig. 3.

Diagrammatic arrangement of the apparatus used in making the observations described in this paper.

pierced by a rectangular hole, and is held vertical by passing through holes in the center of the cross pieces. It is supported in the position of closed circuit by a spiral steel spring *Y*, the lower terminal *B* resting against the fixed contact *D*, in the cast iron bar *H* which passes through the rectangular hole in the square block attached to the end of the rod, while the upper terminal *A* comes in contact with a piston which is inserted in the screw *P*. The cast iron bar is well insulated on both sides by strips of hard rubber, and is supported by stout pillars on a metal

base which is attached rigidly to the frame. The pressure of the piston at the upper terminal of the rod is regulated by a weak spiral spring inserted in piston hole. To avoid the violent jar which results from the sudden stopping of the weight, this part of the apparatus is fixed on a separate shelf attached to the wall. The weight W, which is about 12 kilograms, slides on a brass tube supported independently by a bracket, thus protecting the rod from the downward motion of the weight until it has reached the collar C, the desired point of impact. The collar, or anvil consists of a thick disc of self-hardening steel, fastened rigidly to the rod by a steel set pin and silver solder, and is the fixed origin of the elastic waves set up in the rod by the sudden shock. The impact carries the rod down until the collar reaches the heavy wooden cross piece below. It is held from rebounding by means of a spring latch. The elastic waves on which the operation of the apparatus depends are propagated from C to A and B respectively.

The arrangement of the electrical apparatus is very simple, as will be seen from the diagram, but great care was taken to have all parts highly insulated. The connecting wires are all enclosed separately in small rubber tubing, and then placed side by side in order to avoid self inductance. The battery E consists of three bichromate cells in series, placed on a platform supported by glass insulators. A sensitive galvanometer U, shunted by a low resistance S, served as a check on the constancy of the current in the circuit. The double pole double throw switch T, consisted of hard rubber with platinum contacts, and is operated by means of a long brass rod attached to the armature of a strong electro-magnet placed at some distance from the apparatus. A bank of storage cells supplied the current to work the electro-magnet, which by suitable keys and an automatic interrupter driven by a time clock, could be made to throw the switch T in either one direction, or the other at a given instant. In this way the poles of the condenser K, which is a standard microfarad condenser (Elliot Bros., No. 72) recently calibrated at the Bureau of Standards, was brought into the position of loading, or the reverse; that is across the terminals of the standard non-inductive resistance r, or in series with the galvanometer G, which is a ballistic d'Arsonval of high sensibility.

In taking the observations the manipulation of the apparatus, from the instant the condenser began to load, was entirely automatic; thus eliminating errors from variation in charging time, and otherwise.

The method of procedure was as follows: With the rod in closed circuit, and the weight W in its elevated position, the condenser was thrown into circuit with r at the signal from the time clock, which later, after a

predetermined interval, released the weight. The elastic wave travelling downward then broke the contact B, leaving the condenser to discharge through r until the wave travelling upwards reached the second contact at A; and before either end of the rod had time to regain its closed position the impact carried the rod bodily downward into the position of open circuit. On reaching this position it closed a key at V, which operated the electromagnet, which in turn discharged the condenser through the galvanometer immediately. In this way, using different values for k and r, many sets of observations were taken in quick succession. The results from three different rods, divided in different ratios by the steel collar, are tabulated below, Table I.

TABLE I.

Rod.	r in Ohms.	k in Microfarads.	Log$_e$ Q_0/Q_t.	$t \times 10^6$ Seconds.
L	800	0.05106	0.3818	15.61
L	700	0.05106	0.4383	15.69
L	600	0.05106	0.5038	15.45
L	500	0.05106	0.6206	15.82
L	400	0.05106	0.7701	15.75
M	600	0.05101	0.0988	3.028
M	400	0.05101	0.1484	3.030
M	200	0.05101	0.2964	3.025
N	800	0.05101	0.1570	6.41
N	700	0.05101	0.1814	6.50
N	600	0.05101	0.2110	6.48
N	500	0.05101	0.2502	6.40
N	401	0.05101	0.3148	6.44
N	201	0.10228	0.3118	6.41

The apparatus described here is the result of many efforts to construct one that would function consistently for a given rod. The contacts at A and B were sources of much trouble; platinum, silver, hard steel, German silver, and platinum-iridium terminals were experimented with. The platinum and silver contacts were too soft; the German silver and steel offered contact resistance when used for any length of time, but the platinum-iridium terminals proved to be entirely free from these defects. In the early experiments the inductance in the battery circuit was also a source of disturbance, but this was alleviated by carrying the lead wire from B parallel to the rod, and close to it, through a hole in the collar, and out at A, where the well insulated wires all came together. The consistency with which the apparatus worked finally, is illustrated by a set of observations taken with rod L, Table II.

It will be seen from Table I. that the greatest deviation in time interval, which elapses between the interruption of the currents, in a given rod, at

TABLE II.

$r = 800$ Ohms.		$k = 0.05106$ M. F.	
Galvanometer Deflections, αQ_1.	Galvanometer Deflections, αQ_0.	$\log_e Q_0/Q_1$.	$t \times 10^6$ Seconds.
8.18 cms.	11.98 cms.	0.3818	15.61
8.20	12.05		
8.30	12.20		
8.31	12.12		
8.25	12.09		
8.30	12.10		

the points B and A when different combinations of resistance and capacity are used, is about 2.5 per cent., as compared with the 25 per cent. obtainable with a bullet. In Table II., which is a typical set of observations, the agreement is about 1.2 per cent. If the resistance and capacity be well chosen, for a given rod, a set of observations should not differ from each other by more than 1 per cent.

I wish to express my indebtedness to the late Professor B. O. Peirce for his many helpful suggestions throughout the work, and for the loan of the standard apparatus used in making the observations mentioned in this paper.

THE JEFFERSON PHYSICAL LABORATORY,
CAMBRIDGE, MASS.,
April, 1914.

NOTE ON EVIDENCE FOR ELECTRON ATMOSPHERES.

By F. F. Householder.

IN the Philosophical Magazine for August, 1912, Professor R. W. Wood describes certain experiments in which the electrical resistance of silver films was but slightly changed by a number of transverse rulings, made with a diamond edge, provided the rulings were less than two sodium wave-lengths in width. These results were given, along with others, as evidence for the existence of an atmosphere of electrons extending to a distance of about one wave-length (0.6 μ) from the surface of metals. Though the rulings in question were examined microscopically and seemed continuous, nevertheless lack of continuity, *i. e.*, the presence of metallic bridges across the gaps appeared to be the probable explanation of the observed effects, and it seemed worth while to attempt to prove definitely that this was the case. In repeating the experiments I used film strips only 0.6 mm. wide (much narrower than Wood's), so that the chance of obtaining a continuous cut was greater, and the cut could be examined with greater ease and certainty. The cuts were examined with a Zeiss apochromat objective, n. a. 1.30, oil immersion, and compensating ocular No. 12. The measured magnifying power was 1,500 diameters, and the resolution was improved by using a green light filter. Many strips were ruled without greatly changing their resistance, but in all of these metallic "bridges" were found. Finally the following rulings were obtained:

Strip Number.	Initial Resistance Ω.	No. of Cuts.	Width of Cut.	Final Resistance Megohms.
1	43	1	.6 μ	> 100
2	20	7	.5 μ	> 100
3	6	1	.9 μ	> 100
4	50	1	.5 μ	> 100
5	6	1	.4 μ	> 100
6	50	1	.3 μ	> 100

The conclusion is that if there is an electron atmosphere it's depth is much less than the value assigned by Wood; it must be less than .15 μ.

Department of Physics,
University of Wisconsin,
April, 1914.

WAVE-LENGTH-SENSIBILITY CURVES FOR LIGHT SENSITIVE SELENIUM AND THEIR SIGNIFICANCE.

BY F. C. BROWN AND L. P. SIEG.

IN our last paper[1] we showed that the sensibility curves for one of Giltay's cells was distinct and different from any that had been obtained by other investigators. Since then we have investigated a number of light-sensitive varieties made by Giltay, Ruhmer, Dieterich, and ourselves, and have found the interesting result that selenium as such does not have a characteristic sensibility curve. Such results will be set forth in this paper. Further we shall allude to the fact that the magnitude and position of the maxima of sensibility in the spectrum can be controlled by the treatment of the selenium in the process of making. Incidentally it will be shown that there is an interesting correlation between the change of resistance and intensity of illumination for short exposures no matter what the characteristic curve may be. Lastly we shall indicate the bearing of our results upon the theory of light-action in selenium.

GENERAL CONSIDERATIONS.

The phenomena of light action in selenium are almost unique, and it is for this reason that we should expect any theory of value to incorporate all the diverse phenomena that appear in this element. Of course we shall ultimately wish to explain the conductivity as well as the structure of selenium on the basis of the electron theory. Thus far an analysis reveals that any electron theory that is based on a single type of curve of sensibility is doomed to failure. And as a corollary to this we may say that any electron theory that presupposes only one light sensitive constituent in the selenium is also doomed to failure. For an analysis of exposure and recovery curves for a number of specimens of selenium has revealed that there are at least three components in selenium, at least two of which are acted upon by the light. The results of this paper are quite in agreement with such a complex structure of selenium, although we can not devise the necessary assumptions to determine if the three components are sufficient.

[1] PHYS. REV., N. S., Vol. 2, p. 487, 1903.

Mr. E. O. Dieterich[1] has been led by his researches in this laboratory to believe that the differences in the characteristics of light-sensitive selenium are purely the result of different crystal formations. His argument is very direct and will be presented as soon as his data are completed. Also it may be mentioned that we have produced two new crystal forms of very large size by subliming selenium at the same temperatures at which selenium cells are annealed. This makes it reasonable to assume that these same crystals with perhaps others also are in a more or less stable condition mixed together in light-sensitive selenium.

It is of little avail to select a single sample of selenium made by a particular treatment of the selenium, for the purpose of deducing the nature of light action, because all samples of light-sensitive selenium contain a mixture of certain components, some or all of which may bear direct relations to crystal formations. Any particular pressure, temperature, or time treatment only alters the relative amounts of the components present.

APPARATUS AND METHOD OF MEASUREMENT.

Apparatus.—The general method described in our former paper[2] was followed. The apparatus was improved by the substitution of a Hilger monochromatic illuminator in place of the one by Spindler and Hoyer. In the Hilger apparatus the lenses were 32 mm. or $f/5.6$ in diameter, as compared with the $f/12.7$ of the Spindler and Hoyer apparatus. We were thus able to augment our energy with a given slit width by approximately 5 times. As in the former work the source of light was a Nernst filament kept at practically constant intensity by supplying it with current from storage cells. The filament, while designed for use with 110 volts, was over-volted to about 120 volts, in order to increase the intrinsic brilliancy. The image of the glower was focused upon the first slit of the monochromatic illuminator. In front of this slit was placed a sectored disc, and an optical wedge, either of which, or both could be used to reduce the intensity of the light. The bundle of quasi-homogeneous light coming from the second slit of the illuminator (this slit was kept of the same width as the first one, usually about 0.7 mm.) fell upon a concave silvered mirror. This latter, together with the thermopile, and the selenium cell, was located in a light-tight box. This mirror could be rotated from without, so as to throw the focused image of the slit upon either the thermopile or the selenium. If it was desired to

[1] This work has just been completed and will soon be published.

[2] Loc. cit.

cover the whole cell with diffused light, the cell had merely to be drawn out of focus. Thin glass plates of the same thickness covered the thermopile and the selenium cell.

The thermopile, of the linear Rubens type, was one of the new series-parallel instruments of Bi with an alloy of Bi and Sn, made by Dr. W. W. Coblentz.[1] Its resistance was 2.25 ohms. The galvanometer used with the thermopile was of the Thomson type, made by Siemens and Halske. With its coils in parallel its resistance was 1.35 ohms. The sensibility depended of course upon the period, and with a period of about 6 sec., which we usually employed, its sensibility was about 5×10^{-10} amp. With this thermopile-galvanometer arrangement, a deflection of 1 mm. was obtained on a scale at a distance of 125 cm. when an incident energy of 4.4×10^{-8} watts/mm.^{2} covered the thermopile strip. This latter determination was made with a calibrated carbon lamp at a distance of 2 meters, in accordance with the instructions in the certificate of the Bureau of Standards. In our experiment the area of the focused image of the slit was only 1/7 the area of the thermopile strip. Hence a deflection of 1 mm. in our actual experiments indicated an energy of 7×4.4 or 30.8×10^{-8} watts/mm.^{2} upon the thermopile, and hence upon the selenium cell.[2]

One other device should be described. This was the arrangement by which we could expose the selenium cell at a certain moment, and then throw in the galvanometer for a certain short time. The same device that opened the shutter from in front of the Nernst glower, operated a trigger that released a pendulum. As this pendulum started moving it removed a shutter, thus exposing the cell. As soon as desirable after this operation (usually at once) a key was thrown by this same pendulum thus connecting a galvanometer in circuit. At a certain time later a second key was tripped, disconnecting the galvanometer. The change of resistance could thus be determined by the galvanometer throw for a short interval and at any reasonable time after the exposure of the selenium. The selenium was placed in one arm of the Wheatstone bridge, in which various E.M.F.'s were used. In some cases long exposures were made, but unless otherwise indicated our curves are for mean exposures of 0.4 seconds. In either the long or short exposures we employed the same galvanometer described in our previous paper.

[1] PHYS. REV., N. S., III., p. 59, 1914.

[2] A correction should be made to the footnote of our previous paper, Vol. II., p. 489. While a deflection of 1 mm. meant an energy of 9.3×10^{-8} watts/mm.^{2}, using the total area of the thermopile, the area of the image of the slit was, in this case, about 1/6 of that of the thermopile strip. Then in our previous experiments 1 mm. deflection corresponded to 6×9.3, or 55.8×10^{-8} watts/mm.^{2} upon the thermopile, and hence upon the selenium. So our present arrangement is approximately twice as sensitive as was the former.

As in our previous work, care was taken to adjust for equal energy throughout the observations for each curve. Possibly equal energy is not the proper basis upon which to compare light actions, but at any rate it is the most definite and fundamental basis upon which to work. While equal energies were obtained as determined by the thermopile, the question might nevertheless be raised as to whether equal values of the energy penetrated and acted upon the selenium. If the selenium were selectively reflecting this would be a serious source of uncertainty. However, in connection with a separate investigation we measured the amount of energy reflected from the surface of the selenium in a typical cell for which we determined the characteristic curve and we found that for each wave-length the total reflected energy was only a little more than one one hundredth of that incident of the selenium. Thus it appears that a selenium cell is a fairly good black body. We shall deal with the optical properties of selenium in a separate paper.

Effect of Varying Slit Width.—As is well known, the beam of light from a monochromatic illuminator is only a quasi-homogeneous beam, and its non-homogeneous character becomes more and more evident as the red end of the spectrum is approached. Any curves for such an apparatus can be corrected with considerable definiteness[1] for the slit width, although the calculation is rather a laborious one. In view of the labor involved in the calculation, it was thought best to try first an experiment to test the extent of the inaccuracy that arises from the use of a finite slit width.

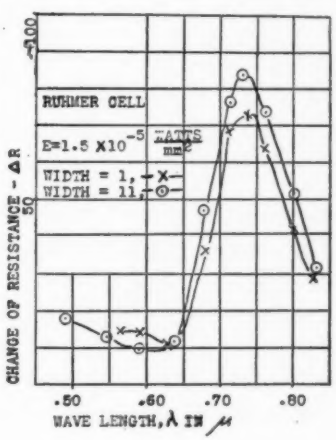


Fig. 1.

Fig. 1 represents the results of this experiment. The two curves are clearly indicated in the figure, the one for a very narrow slit with (about .14 mm. on both the collimating and focusing telescope) and the other for the unusual slit width of about 1.5 mm. The slit width was thus varied by about a factor of eleven. By means of the rotating sector the energy intensity was lessened to correspond to that of the narrow slit, thus giving the same change of conductivity in the selenium at wave-length $\lambda = .64\ \mu$. There is no special significance to be attached to the slight variation of the magnitude of the maximum. It merely indicates that there are small outstanding errors that nullify any necessity for

[1] Paschen, Ann. d. Phys., 60, 712, 1897.

making slit width corrections. Having justified the use of such a wide slit width, we believe ourselves perfectly secure in our results which were usually obtained with slit widths of 7 mm. This gave us a maximum of energy with a negligible error from spectral impurity.

Effect of the Order of Exposure.—Thinking that the shape of the curves might vary slightly with the order of exposure to the light of varying periodicity, an experiment was tried the results of which are shown in Fig. 2. First a curve was taken for a Ruhmer cell by the usual procedure, *i. e.*, by measuring the sensibility at the shortest wave-length first and then proceeding step by step to the reading for the longest wave-length. Then this procedure was exactly reversed by taking the sensibility for the longest wave-length first and going backward. We concluded from these curves and a number of other cases where it was advisable to check readings that the order of exposure made no material difference. However, a little greater reliability was attached to the first order of exposure. The curves given in this paper are substantially correct. After readjusting our apparatus and replacing some of the cells, we were able to duplicate results with surprising accuracy.

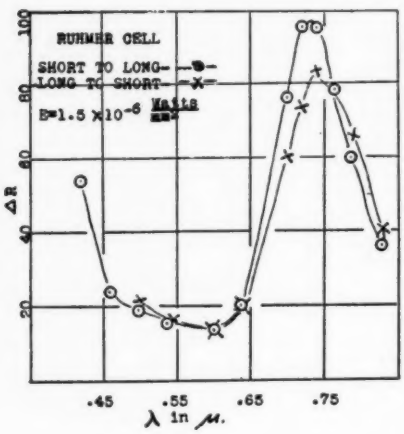


Fig. 2.

THE CHARACTER OF THE SENSIBILITY CURVES.

General.—When this work was begun it was believed that sensibility-wave-length curves obtained by using short exposures should for all varieties of selenium show the same characteristics, providing that the rapid changes in selenium always arise from a common light-action on one component of the selenium. Or conversely it was believed that the sensibility curves should be complex, providing that the rapid changes in the selenium by light arise from action on two or more components of the selenium with widely varying rates. It is the converse view that naturally suggests itself following the analysis made by one of the authors.[1]

Fig. 3 shows the various types of sensibility curves which we have obtained with different samples of selenium, and we do not claim to have exhausted the list. The observed changes of resistance recorded on each

[1] PHYS. REV., 33, p. 403, 1911.

curve were taken for exposures of equal intensity, wherever we found that the form of the curve was materially affected by change of energy. The scales for each curve are however arbitrarily chosen, so that the maximum ordinate of each curve lies at about the value 100. Thus the curves serve a purpose resembling a spectrum analysis of an element. The intensity of the lines can be compared with the lines of the same spectrum in order to establish the character of the unknown. In spectrum analysis the amount and the temperature of the element producing the spectrum are matters of secondary importance. Just so the curves in Fig. 3 are characteristic curves, but they neglect to bring out the absolute or even the relative sensibility of the different samples of selenium. The chart accompanying the curves gives the names of the types of cells used and also the energy intensity that resulted in the indicated curves. However it is rather unusual for the character of the curves to change with varying intensity such as had been previously observed both by Pfund[1] and ourselves.[2] Only two of the curves in Fig. 3 showed such a variation. In some instances tests showed the character to be only imperceptibly changed by intensity variations of the ratio of 50 to 1. Furthermore we found that the character of the curves was not necessarily much affected by the duration of exposure. Only two of the eight samples, whose curves we are discussing, showed such large variations. This also is new.

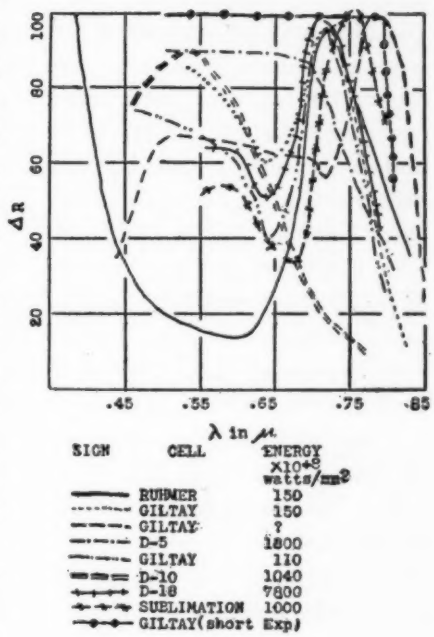


Fig. 3.

It is obvious that there is no characteristic curve to be found by the method of procedure that we followed. A Ruhmer cell in vacuum indicated a maximum in the ultra-violet too far out for us to locate, and another maximum at .72 μ. This selenium had a broad minimum extending from .55 μ to .62 μ. Recently Mr. Dieterich has succeeded in producing two samples of selenium with a maximum near the ultra-

[1] PHYS. REV., 34, p. 370, 1912.

[2] Loc. cit.

violet. But with these exceptions all samples which have come to our notice decrease more or less precipitously in their sensibility back of .5μ. Many specimens have the indicated maxima at about .7 μ, but this maximum wanders all along to .8 μ, and in the typical Dietrich cell, as indicated in our paper by the letter *D*, this maximum dwindles or disappears altogether. Stated briefly the maximum that so frequently appears in the red, may be controlled both as to its location and its magnitude even to its disappearance. One cell has shown considerable sensibility out as far as .85 μ. Similarly as regards the minimum, which usually occurred about .64 μ. In the Ruhmer cell it occurred back as far as .6 μ and in the selenium whose crystals were deposited by sublimation in a high vacuum, it occurred at .68 μ and in one other cell at even longer wave-lengths. In one of Giltay's cells and also in one of Mr. Dieterich's cells, the fourth and ninth curves respectively in the chart, the minimum did not appear at all. At about .55 μ there was usually a broad maximum but it is observed that this region may contain a broad minimum as well.

Without any further work the conclusion seems obvious that light produces more than one action in the selenium, or in other words there is more than one component or kind of selenium if you please existent simultaneously in the selenium cell.

The Giltay and Dieterich Types.—While it is true that both Giltay and Dieterich do make cells of widely varying character, it is nevertheless true that all of Giltay's cells of which we have any knowledge have a pronounced maximum at .69 μ or beyond and a more or less well-defined one in the region of .55 μ. On the other hand Dieterich's samples usually have a very pronounced maximum about .55 μ, and a controllable maximum in the red which may be entirely eliminated by the method of making. This so called Dieterich type is shown by curve *D*, Fig. 4, where the energy intensity was 6.6×10^{-6} watts per mm.^{2} For greater or less illumination intensity, the character of the curve was as far as we could determine identical to this one. In the same figure, the curves G_1 and G_1' are for a typical Giltay cell, where the intensity of illumination varied by a factor of 20 to 1. It is common for the Giltay cells to maintain the same character unaltered for widely varying intensities, just as these curves indicate.

The Effect of Varying Electrical Intensity.—Since it has seemed advisable to regard the selenium as in a state of equilibrium under the action of a number of forces, it is reasonable to expect that an alteration of any one of these forces might alter the form of the sensibility curve. We have yet to test this point particularly for the varying temperature conditions. An examination of the voltage effect shows that the char-

acter of the curve is only slightly altered, while the sensibility is uniformly and materially altered in magnitude. The curve in Fig. 5 indicated by circles shows the characteristic curve of cell D7 for an intensity of 0.1×10^{-5} watts per mm.^{2}, when exposed for 30 seconds. There was a potential difference of 3.5 volts across the selenium. Next this was changed to 0.5 volts and the intensity altered till it produced the same change of resistance at .45 μ as was produced with less intensity and

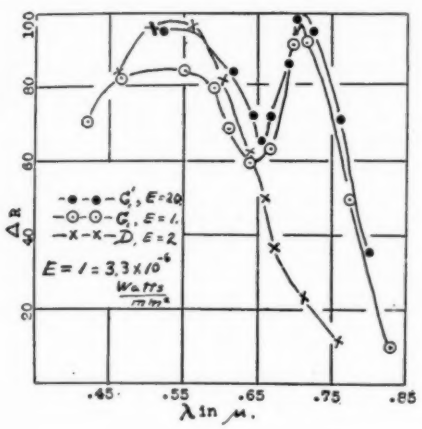


Fig. 4.

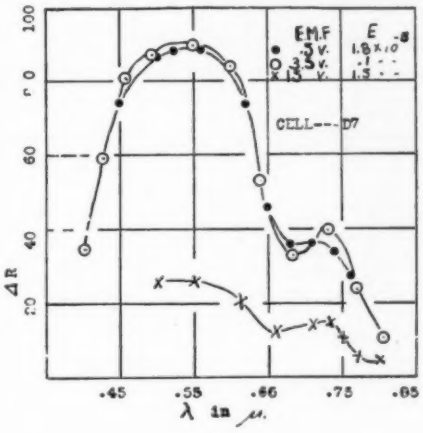


Fig. 5.

greater potential. With this intensity which was 18 times greater the curve indicated by solid dots was obtained. It is to be noted that altering the intensity by a factor of 18 to 1 had the same effect as altering the potential by a factor 7 to 1. However it must also be noted that while the deflections were nearly identical for the sake of comparison, that the absolute change of resistance was only about one seventh in the second case of what it was in the former.

It may be estimated that a change of potential of the order of 50 to 1 will so balance the selenium in this cell that the same absolute change of resistance would be produced when the intensity of illumination is varied by a ratio of 18 to 1. The conclusion is that for this cell the alteration of the electric intensity alters the character of the curve only slightly, but that it makes a large difference in the absolute change of resistance by light. This last point has also been verified in former papers. The lower curve in the figure is for short exposures, and with 15 volts across the selenium. Thus changing the duration of exposure, the electrical intensity and the light intensity does not alter the character of the curves to any definite and marked degree in this particular cell.

The Maxima are Inherent in the Selenium.—Since the well-known

experiments of Pfund and Berndt no one has questioned that at least a great part if not all the light sensitiveness of selenium is in the selenium structure itself and not because of some impurity or selenium compound. Yet when different samples show such widely varying characteristics, the question may well be raised again as to whether impurities do not play an important rôle in prescribing the characteristics. Mr. Dieterich is obtaining a large amount of evidence to prove that impurities are of very secondary importance if they enter at all. One point that may be mentioned is illustrated in Fig. 6. He took a Giltay cell marked "normal G" and subjected it to purely physical treatment, after which the characteristic curves were of the form indicated by curves E_1 and E_{10}, where the illumination intensity varied by a factor of ten. By this treatment which he will relate in detail, the Giltay cell was transformed into a Dieterich cell. It is also worthy of note that the character of the curves was unchanged by a variation of the intensity by a factor of ten. As has been previously pointed out, the selenium components seem to be put in a dynamic equilibrium in the process of making the cell under the action of a number of forces such as heat, and pressure treatment, and further, these components are maintained in equilibrium under a number of forces such as pressure, temperature, illumination, absorbed materials, electrical stress and the crystal formation itself.

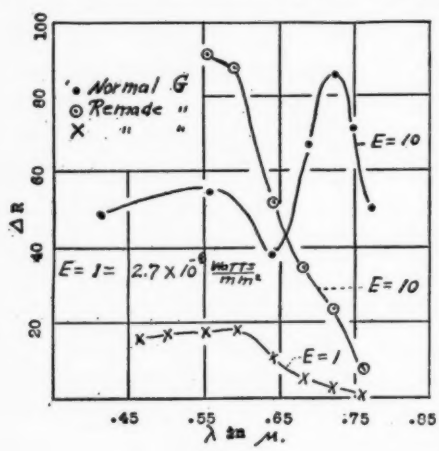


Fig. 6.

That the characteristics of any given specimen are inherent in the selenium itself is yet further verified by the fact that the maximum in the red can be put in or eliminated at will by the heat treatment. And it is expected that the exact conditions will soon be discovered which determine the presence or absence of the maxima in the shorter wavelengths of the visible spectrum and even in the ultra violet. The curves in Fig. 7 are taken from Mr. Dieterich's samples. The remarkable difference in these curves arose solely from the difference in heat treatment during the process of making. In fact he can predict almost without failure what will be the character of a given sample of light-sensitive selenium. It should be noted that the intensity of illumination was the same for all curves in Fig. 7.

The Variation of the Sensibility.—Generally the light sensibility of selenium is regarded as a function of the amount of selenium that has been transferred from the amorphous to the crystalline state. And yet it seems perfectly futile to attempt to explain the enormous variations in sensibility on this basis. The variations so greatly outnumber the possible combinations. Mr. Dietrich has been able to vary the sensibility over a very wide range without altering the character of the sensibility curve, but there seem to be a number of factors entering into the exact control, only a part of which he is aware of. Nevertheless

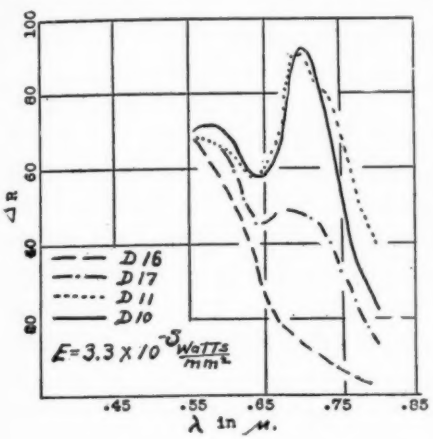


Fig. 7.

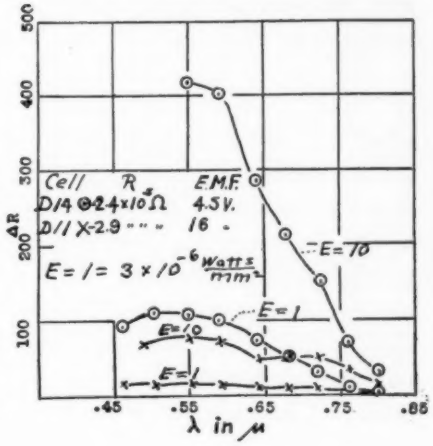


Fig. 8.

he has produced a low resistance cell which shows an effective sensibility at .59 μ about ten times greater than that of any Giltay cell in our possession. Its character is shown by the curve *D*14, Fig. 8, for two intensities varying by ten to one. And again starting with a sample of the same amorphous selenium and proceeding differently with the treatment he produced a cell *D*11 which had about the same specific resistance in the dark and only a slightly different characteristic curve, but its sensibility as can be learned from the curves was only about one twentieth of that of cell *D*14. In making this deduction an allowance must be made for the lower voltage used with cell *D*14.

THE VARIATION OF SENSIBILITY WITH INTENSITY OF ILLUMINATION.

Quite recently Nicholson[1] has made a very able mathematical analysis of certain phenomena in selenium on the basis of one electron theory. Without discussing the reasonableness of his assumptions, it may be of interest to test some of his deduced equations over a wider range than

[1] PHYS. REV., N. S., Vol. 3, p. 1, 1914.

was done in his work. He used only two varieties of selenium and he was only prepared to take exposures as short as 12.5 seconds. In applying his results to his theory he presumed that an exposure of such duration was equivalent in its effect to an instantaneous exposure. We are inclined to doubt this presumption. Our results should have the advantage that comes from a study of a larger number of varieties of selenium and also the advantage of exposures of 0.4 second duration, which more nearly approximate instantaneous effects.

The most critical test of Nicholson's theory perhaps lies in the derived relation between the change of conductivity and the intensity of illumination. This relation is expressed by the equation,

$$d = D \cdot I^{\beta},$$

where d is the change of conductivity, I is the intensity, and D and β are constants. According to Nicholson's theory β should have the value $\beta = 1/2$ for instantaneous exposures in the shorter wave lengths and $\beta = 1$ for the red and infra red, and $\beta = 1/2$ for unlimited exposures throughout the spectrum. The above equation was originally set up as an empirical equation by Pfund.[1] We find justification for the use of the equation when used as an empirical one and applied to any given cell, but we can not see that the simple assumptions regarding absorption, reflection and resonance as given in Nicholson's paper, are sufficient to

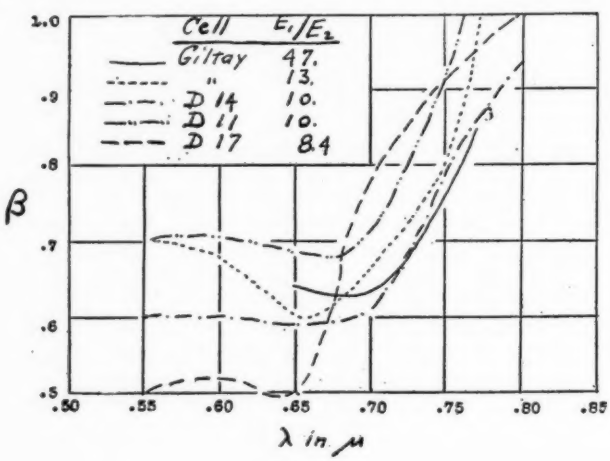


Fig. 9.

explain the varying values of β in the different samples of selenium, nor the variations in a given sample. It must be remembered that the constant β occurs as an exponent, and consequently small deviations in its

[1] PHYS. REV., Vol. 34, p. 370, 1912.

value are of relatively greater importance than relative errors in a multiplying or additive constant.

The manner in which β varies for exposures of 0.4 second for a number of different samples of selenium is shown in Fig. 9. It is rather interesting that cells which gave such widely varying characteristic curves (see Figs. 3, 7, and 8) should show such a general likeness in the variation of the constant β, for the different periodicities of light. It is observed then that β varies in a general way between .5 and 1 for short exposures.

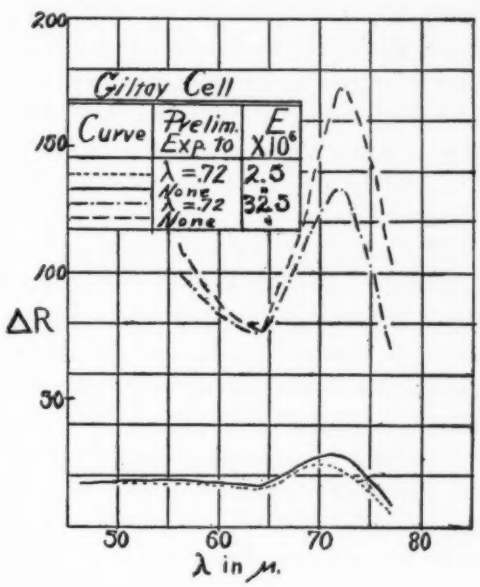


Fig. 10.

An attempt was made to discern whether any change in the light sensibility curve would result if before each wave length-deflection reading was taken, there was made a preliminary exposure to a fixed quantity of energy from a beam of light of a given wave length. Nicholson made exposure tests similar

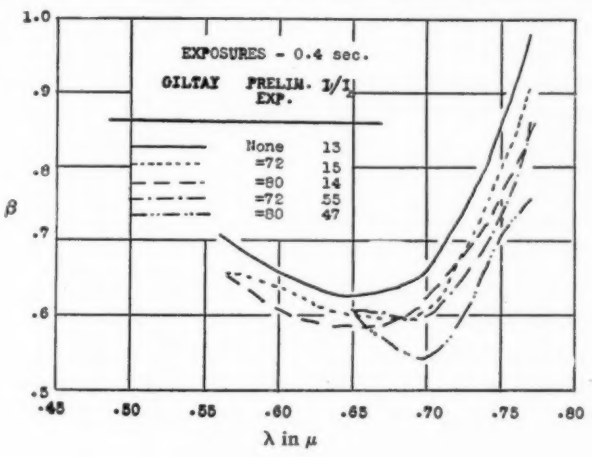


Fig. 11.

to this except that instead of making the additional exposure a preliminary one he left a steady exposure on the cell while he was

running a curve. In both cases the effect is much the same, and has the tendency to blot out the effects due to slow changes of resistance accompanying light-action. The effect of the preliminary exposure was slightly to iron out the maximum. However, the curves relating β and λ are not materially altered by the preliminary exposures. The first of these two results is shown in Fig. 10, connecting the change of resistance and wave-length; and the second point covering the variation of β and λ is shown in Fig. 11.

CONCLUSIONS.

The analysis made some time ago on the basis of the rates of change in the selenium, showed the structure of the selenium to be complex, consisting of three components in the specimens studied. Now we have made an analysis on an entirely different basis, that of the character of the sensibility curves, and our analysis reveals again a structure at least as complex as that revealed formerly by other samples of selenium. We are not yet able, however, in the latter analysis to set up a simple set of postulates whereby we can subject our analysis to a mathematical test as was done formerly. As far as can be seen our analysis requires at least two separate light actions in the selenium.

No doubt the action of light in any of the components is of such a nature that electrons are made free when one component changes to another, because the former analysis into several varieties of light sensitive selenium required that electrons be made free but in no case did it require the recombination of electrons. Knowing that the structure of light sensitive selenium is complex, and knowing what we do about the nature of this complexity we should now perhaps be in a position to apply the electron theory to an explanation of the phenomena.

We have isolated a number of new crystal forms of selenium by sublimation of selenium in a high vacuum. The conditions which determine what kind of crystals will form must be very definite, for we have had very large crystals of different forms grow up within a millimeter distance of each other where the temperature and pressure could not have varied greatly. In free unhampered space some of these crystals have a length of more than ten millimeters. We know of four formations of crystal selenium that are doubly refracting when formed in a vacuum. Whether the crystals in the selenium cell are doubly refracting we are not quite sure, and yet one cell made by the formation of crystals directly from the vapor state must have contained some doubly refracting crystals. The point that we wish to make here is that crystals which are directive in their structure towards light should also be directive in their electrical

properties and if these crystals are instrumental in the conduction they should alter the conductivity differently depending upon their positions. If so we must in explaining the light sensitiveness of selenium allow for the formation of crystals either with axes pointed promiscuously or in consistently varying directions. Add to this a mixture of crystals in more or less stable equilibrium as to form and position and we have we believe a basis on which all the light electric properties of selenium may be worked out.

Previous results on the effect of abrasion[1] and on the pressure effect on the electrical conductivity indicated in a very marked degree that the slow changes accompanying light-action were the result of crystal changes. There was doubt concerning the seat of the rapid changes. It was conceded that perhaps light might expel electrons from the atoms in the transformation of one component to another. If in this present work we had found a single or slightly varying position of maximum spectral sensibility, we might have been justified in concluding with Pfund and others that the primary thing is the liberation of electrons from atoms of selenium. But if there is one significant conclusion that can be accepted as a result of the variation of the sensibility curves, it is that light does not act on the atoms as units. Rather a larger unit, no doubt of the order of a crystal unit, is the seat of the disturbance by light action. We are compelled to recognize crystal boundaries when dealing with the flow of electrons in selenium, possibly also in other elements. Otherwise there is no apparent basis for the unification of our knowledge.

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THE UNIVERSITY OF IOWA.

[1] Phys. Zeits., Nov. 15, 1912.

HIGH TEMPERATURE MEASUREMENTS WITH THE STEFAN-BOLTZMAN LAW.

BY C. E. MENDENHALL AND W. E. FORSYTHE.

INTRODUCTION.

IN view of the increasing use of extremely high temperatures (2000–3000° C.) the establishment of a reliable scale of measurement for this region becomes increasingly important. In almost all cases some form of radiation measurement is the most convenient if not the only possible method to use. At the hands of Day and Sosman[1] gas thermometry seems to have been pushed about to its limit in determining the melting point of palladium (1549° C.), and it is naturally desirable that the method used for extending the range should be something better than mere extrapolation of an empirical curve. There are four well-known radiation formulæ (for a perfect radiator) which might be available for this purpose:

(1) $\int_0^\infty E_\lambda d\lambda = S = aT^4$, Stefan-Boltzman law of total radiation.

(2) $\lambda_m = bT^{-1}$, } Deductions from Wien's displacement law.

(3) $E_m = KT^5$, }

(4) $\log E_\lambda = K_1 - \frac{C_2}{\lambda}\frac{1}{T}$, Wien's distribution law.

Of these, the last, (4) is usually the most convenient to use, being the basis of optical pyrometry, but its theoretical foundation is so uncertain that it amounts only to an empirical formula. The theoretical basis of (2) and (3) is certainly much better, but (2) evidently gives a very insensitive method, particularly at high temperatures, while the experimental use of either (2) or (3) involves complicated apparatus and extended observations. On the other hand (1) has the most simple and sound theoretical basis and can be very simply but accurately applied. There are in fact several well known "total radiation" pyrometers on the market, but these are usually calibrated empirically; and unless proper precautions are taken the method is liable to serious error. In connecting any one scale of measurement to another it is always desirable

[1] American Journal of Science (4), 29, 93, 1910.

to compare them in the region in which they overlap, even though we are assuming that the two scales determine the same fundamental quantity, in this case *absolute thermodynamic temperature.* Hence the following work may be considered in three parts: (1) A comparison of the Stefan-Boltzman scale of temperature with the Day and Sosman gas scale between 1063° C. and 1549° C., the melting points of gold and of palladium. (2) A determination of the melting point of platinum in terms of the *S–B* scale. (3) A comparison of the optical temperature scale based on the application of Wien's law to a pyrometer of the Holborn-Kurlbaum type, with the Stefan-Boltzman scale up to 2820° C. Such a comparison has been carried out heretofore by Lummer and Pringsheim[1] up to about 2000° C., at which temperature their total-radiation temperature measurements involve discrepancies of nearly 20°, while their optical scale differs from the other by 10° or 15°. Gillette[2] has compared the two scales up to about 2500° C., and states that they "are in agreement," but does not state how good the agreement was, nor how accurately either of his two scales could be reproduced; from some figures he quotes it seems fair to infer that discrepancies of 10° in the neighborhood of 2200° C. were to be expected. In the work here described we have extended the range and considerably increased the accuracy.

Arrangement of Apparatus.—(*a*) Optical pyrometers. These have already been described,[3] though the spectroscopic eyepiece referred to in that article was not used in the present work; instead two eye screens of Schott No. 2,745 red glass each 3.37 mm. thick were used, giving a rather broad transmission band (200 A. U.) with center at $\lambda = 0.658\ \mu$ as determined by spectro-photometric measurements using radiation characteristic of about 2000° C. These instruments were calibrated by observations on black body furnaces held at the melting points of palladium and gold respectively. For the intermediate points and for extending the scale rotating sectors of known aperture were used, combined with equation (4) above, in which C_2 was taken as 14,500, and λ as $0.658\ \mu$. The optical pyrometer was calibrated once before beginning the work and once near the end; the two calibrations were in close agreement, but as there had been a long interruption in the work the first calibration is used for all points up to 2500° C., the last for the 2820° C. point. The pyrometer lamp filaments were of untreated carbon, of such size that a change of about 0.500 amperes in the lamp current corresponded to a change of 500° C. (from the melting point of gold to that of palladium). The lamps were never used above the apparent palladium temperature

[1] Lummer & Pringsheim, Verh. Deut. Phys. Ges., 1, p. 3, 1903.

[2] Gillett, Journal of Physical Chemistry, 15, p. 213, 1911.

[3] PHYS. REV., July, 1911, p. 74, Vol. XXXIII., No. 1.

but were aged for 30 hours at a considerably higher temperature. The angular aperture of all the sectors used is known with sufficient accuracy for the present purpose, since the computed temperatures of the extended scale are but little affected by small variations in the aperture of the sectors. For example the most difficult sector to make, the "1/180" was found on measurement to have an opening of 2° 1′ 50″, but this departure from 2° made a difference of only 5° C. in the temperatures computed to extend the scale from 1549° C. to about 2800° C.

(*b*) With this method of calibration only one known fixed point is needed, to which all temperatures are referred; this is the melting point of palladium (1549° C.) as determined by Day and Sosman.[1] This temperature and the melting point of gold were reproduced in the laboratory by melting short strips of the metals held between platinum wires in electrically heated black-body furnaces provided with Pt-Pt Rh thermocouples. The thermocouples were merely for use in controlling the temperatures during the optical observations. Melting was indicated by an electrical signal. One black body was the standard form with diaphragms blackened inside; the other was made up of magnesia tubing and plate, with suitable diaphragms. No difference was found between the two. The gold used was the best from Eimer and Amend—the palladium the purest possible to obtain from Hereaus.

(*c*) The black body furnace and attachments for high temperature observations are shown in Fig. 1. Part of this apparatus has already been described.[2] The black body is a graphite tube (*T*) of 14 mm. inside diameter, 3 mm. walls and 30 cm. length, provided with a graphite diaphragm (*G*) placed 1 cm. away from the center, as shown. Hence one might expect better black body conditions in the longer segment of the tube, which was the only part used for primary observations. A glass window (*W*) opposite the short section permitted optical observations for purposes of control. A series of water cooled diaphragms D_1, D_3, D_4, D_5, served to protect the total radiation thermopile *P*, and a moveable water cooled diaphragm D_2, not only served as a shutter but contained the real limiting aperture *A*, which could be brought to a definite axial position against a stop. The geometric proportion was such that the pile *P* received radiation only from the graphite diaphragm (*G*) in the furnace.

A fundamentally important point is of course the accuracy with which the graphite tube furnace realizes black body conditions. Since graphite itself is a good radiator (having a reflecting power of only 21 per cent.

[1] Loc. cit.

[2] Forsythe, Astrophysical Journal, 34, 353, 1911.

for red light at 2000° C.)[1] the importance of having a small ratio of aperture to surface of uniform temperature, is less than with a metal tube having a lower emissive power. The ratio of length to internal diameter of our tubes was greater than that frequently used with black body furnaces, which is an advantage. Our evidence for good black body conditions is two fold—first the satisfactory results of our comparison of the *S–B* scale with the gas scale (see below), and second a simple experimental test concerned with visible waves only. This consisted in drilling into the diaphragm *G* one or two fine holes, which would act as cavities within a cavity. The fact that these were not distinguishable from the plane face of the diaphragm is decided evidence in favor of good black body conditions.

The window W_2 above the thermopile allowed optical observations

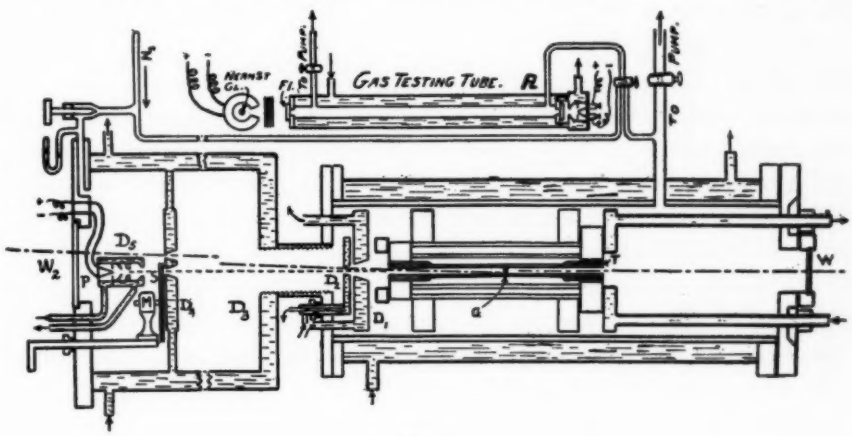

Fig. 1.

to be made on (*G*) when the aperture in D_2 was slightly displaced from its central position. Hence though optical and total radiation measurements of temperature could not be made simultaneously, they were at least made upon the same surface thus avoiding direct errors due to temperature differences in the furnace. All this careful screening not only eliminated stray radiation but also resulted in a very stable zero for the thermopile. The small motor *M*, mounted on a rod movable from the outside, carried a sector directly on its shaft. When the sector was swung up in front of the pile the radiation from the furnace was reduced in a known ratio depending upon the clear aperture of the sector. The sectors, made of two sheets of brass touching only at the center, to avoid the effects of absorption and re-radiation to the thermopile, were of such a size that two different apertures could be cut in each disc.

[1] Mendenhall and Forsythe, Astrophysical Journal, June, 1913, p. 380.

The receiving thermopile consisted of a single junction of Bi-Sb and Sb-Cd alloys, the "hot" junction being soldered to a very light receiving disc of silver foil, 3 mm. in diameter, a similar disc being on each "cold" junction, where the alloys joined the copper lead wires. To still further reduce the drift of zero the water flowing immediately around the thermopile was passed through a large barrel of water, the thermal capacity of which effectively damped out small fluctuations. The receiving disc was blackened with acetelyne smoke as suggested by Coblentz, and mounted at the center of a hemispherical silver concave mirror according to Paschen. Under these circumstances the receiver has been assumed to be a perfect absorber, since only differential errors would be introduced if this assumption were not quite correct. The thermopile was connected in series with a low resistance Ayrton-Mather D'Arsonval galvanometer, and a resistance box for reducing the sensibility.

The necessary temperature correction to allow for the absorption and reflection of the glass window W_2, was carefully determined at one temperature, and computed for all others by using equation (4). Before the Stefan-Boltzman law can be legitimately applied it is necessary either to eliminate or determine the absorption of the gases in the furnace. The most dangerous constituents are water vapor and carbon dioxide. It was not desirable to work at very low pressure, since for one thing, it is difficult to maintain such pressures constant because of the gases given off by the hot parts of the furnace, and the sensibility of the thermopile is a rapid function of the pressure at low pressures. Furthermore the evaporation of the graphite tube is more rapid at low pressures. For these reasons a pressure of from 5 mm. to 15 mm. of mercury was used. In order to reduce as much as possible the danger from gas absorption, a steady stream of nitrogen was maintained at all times through the furnace. This was obtained by passing air over moist KOH, through a drier, over red hot copper turnings, and then again over KOH and P_2O_5. Exhaustion was maintained by a Fluess and a Gaede box pump. With steady pumping on the one hand and a graduated pin-valve controlling the inflow of nitrogen on the other, it was possible to maintain a pressure constant to within 0.2 mm. as indicated on a large mercury gauge observed microscopically. It was chiefly important that observations which were to be compared should be taken at the same pressure. The flow of the nitrogen was *from* the pile through the furnace tube. In order to test the absorbing power of the gas, the tube R (Fig. 1) was so arranged that it could be either exhausted or filled with gas from the main furnace tube. The ends of this testing tube were closed with fluorite plates, opposite one of which was a Nernst glower and opposite the other a

thermopile. It was necessary that these should be outside the testing tube, in order that they might be unaffected as to temperature and sensiblity respectively, by changes in the gas content of the tube. The method of testing the gas was simply to compare the deflections produced by Nernst radiation transmitted through a vacuum (or low pressure nitrogen) and through the furnace gases, the current through the Nernst being maintained constant. In this way a very small loss by absorption could be detected, since the deflections were of the order of 30 cm. and could be read to 0.2 mm. It was always found that if the furnace was washed sufficiently at a high temperature by a stream of nitrogen, the absorption loss was negligible, not more than one tenth of one per cent. It may be objected that the gases in the furnace were hot while those tested were cold—but this would at least result in breaking down CO_2 to CO in the furnace, which would reduce the absorption.

Reduction of Observations.—Stefan-Boltzman Scale. If a certain deflection D of the thermopile galvanometer is obtained at a temperature T_1 abs. (always the gold or palladium melting point), with clear aperture, and the same deflection is obtained through a rotating sector, whose transmission ratio is $S(< 1)$, at a temperature T_2 (abs.) then

$$T_2 = \frac{T_1}{\sqrt[4]{S}}.$$

If it happened that the two deflections were not exactly the same (they never differed by more than a few parts in a thousand), it was assumed that the deflections were proportional to total radiant energy. The temperature of the shutter used to cut out the radiation from the furnace does not enter into the problem, because it and the rotating sector were at practically the same temperature.

Wien Scale.—If a current i in the pyrometer lamp gives photometric balance against a black body at temperature T_1 with clear aperture, and also at temperature T_2 through a sector of transmission ratio S, then

$$\log \frac{1}{S} = \frac{C_2 \log e}{\lambda}\left(\frac{1}{T_1} - \frac{1}{T_2}\right),$$

where T_1 and T_2 are the absolute temperatures in degrees Centigrade. To the value of T_2 determined from this equation must be added a correction for the absorption of the glass through which observations were made. This was independently determined and applied.

Results 1.—Comparison of Stefan-Boltzman and gas scale between 1063° C. and 1549° C. (Table I.). Twelve comparisons[1] were made.

[1] Each comparison involved an independent set of observations and independent determination of the fundamental points.

TABLE I.

SUMMARY OF TOTAL RADIATION DATA AT 1063° C. AND 1549° C. (GAS SCALE) AND 1755° C. ON THE OPTICAL SCALE.

1. Date.	2. Def. at 1063° C.	3. Def. at 1549° C.	4. Ratio 3/2.	5. Def. at 1755° C.	6. Ratio 5/2.
5–21	29.28	29.33	1.002	29.18	0.996
5–22	29.08	29.17	1.003	29.08	1.000
5–24	29.85	29.87	1.000+	30.03	1.006
5–26	29.77	29.97	1.007	30.04	1.008
5–29	29.37	29.32	0.998+	29.27	0.997
5–30	30.45	30.44	1.000−		
6– 1	29.89	29.92	1.001	30.11	1.007
6– 2	29.33	29.34	1.000	30.01	[1.025][1]
6– 3	29.33	29.33	1.000	29.47	1.005
6– 5	28.79	28.79	1.000	Mean.....	1.003
6– 7	28.29	28.27	0.999		
6– 9	28.27	28.25	0.999		
		Mean.....	1.001		

[1] Rejected, because conditions became unsteady.

TABLE II.

SUMMARY OF TOTAL RADIATION DATA AT 2212° C., 2489° C. AND 2500° C. ON OPTICAL SCALE.

1. Date.	2. Approx. Temp., Opt. Scale, °C.	3. Def. at 1549 °C, Cm.	4. Def. at Temp. 2.	5. Ratio 4/3.
5–24	2212	32.26	32.15	0.996
5–26	2212	31.90	31.86	.998
5–29	2212	31.51	31.46	.998
5–29	2489	31.51	31.45	.998
6– 1	2212	32.16	31.98	.994
6– 2	2212	31.92	31.95	1.000
6– 3	2212	31.11	31.06	.998
6– 3	2489	31.11	31.08	.999
6– 5	2212	31.40 (At 1755° C.)	31.34	.998
6– 7	2500	32.67	32.63	.998
	Mean ratio for 2212.....			.997
	Mean ratio for 2489 and 2500.....			.998+

TABLE III.

SUMMARY OF OPTICAL PYROMETER READINGS (CURRENT IN LAMP) AT 2820° C. ON S.-B. SCALE.

Date.	Opt. Pyr. Reading, Amps.	Date.	Opt. Pyr. Reading, Amps.
1–19	1.077	2– 7	1.080
2– 5	1.079	2–12	1.080 +
Mean.....			1.079

The total-radiation sector having been cut in the ratio $[(1063+273)/(1549+273)]^4$, the ratio of the corresponding deflections should have been unity; the observed mean ratio was 1.001, the maximum ratio being 1.007 and the minimum 0.998. This indicates an agreement within the possible errors of experiment, which are about $\pm 0.5°$ C. at each point. The accuracy is limited by the optical rather than the total radiation measurements.

Results 2.—The melting point of platinum. Our value for this depends on three very concordant direct determinations of the melting point in a graphite tube black body furnace, carried out by Mr. C. G. Peters. The platinum was enclosed in porcelain and protected from the action of reducing gases by a flow of nitrogen. Mr. Peters's single transfer of this result to the *S–B* scale gives 1755° C.; our repeated transfer gives 1753° C. which should be given more weight. The indication is that the present accepted[1] value of 1753° C. is not far off. The individual determinations differed by less than a degree. This determination will be repeated, as it involves difficulties and uncertainties not present in the remainder of the work.

Results 3.—Comparison of the Stefan-Boltzman and Wien scales (Tables II. and III.). Comparisons were made at four temperatures as follows:

TABLE IV.

Number of Comparisons.	Temperature.	$T_W - T_{S.B.}$	Range of Observations.
9	1750° C.	less than $\pm$ 0.5° C.	
7	2200	less than + 2	2° C.
3	2500	about + 2	4
4	2820	about + 4	7

These differences may all be taken as not greater than the experimental error, but it is noticeable that they show a definite trend with temperature. To bring the two scales into agreement it is only necessary to assume a slightly different C_2 or λ; a change from 0.658 μ to 0.657 μ would accomplish the result, and this change is probably less than the uncertainty in the knowledge of λ. The uncertainty in the knowledge of λ prevents any final conclusion being drawn as to the value of C_2. The equipment is now being used in conjunction with a spectroscopic pyrometer especially for the accurate determination of C_2.

[1] Day and Sossman, Journ. de Physique, 2, Ser. 5, 899, 1912.

SUMMARY.

The Stefan-Boltzman law has been used with greater accuracy than heretofore to extend the high temperature scale to 2820° C. and the optical scale based on the use of Wien's law with $C_2 = 14{,}500$ and $\lambda = 0.658\ \mu$ (for Jena glass 2,745) has been shown to be in very close agreement with the total-radiation scale. The total-radiation scale has been compared with the Day and Sosman scale between 1063° C. to 1549° C. and found to agree with it to at least 0.5°. Three determinations of the melting point of platinum gave the result 1753° C. on the *S–B* scale.

DEPARTMENT OF PHYSICS,
UNIVERSITY OF WISCONSIN,
February, 1914.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

METHODS OF MEASURING TIME CONSTANTS OF LOW RESISTANCES.[1]

BY FRANK WENNER, ERNEST WEIBEL AND F. B. SILSBEE.

ALL values heretofore obtained for the residual inductance of "non-inductive" standards of low resistance have been based upon the calculated inductance of some conductor. This calculation of the inductance from dimensions involves serious assumptions as to current distribution, inductive effects in potential leads, etc.

The first method discussed below gives primarily the sum of the time constants of the two resistances used. By using three resistances three sums can be measured from which each time constant can be obtained, without calculation of the inductance of a resistance standard. In this method the resistances are each connected in series with a mutual inductance as indicated in the figure and excited by alternating currents substantially in quadrature. The constants of the circuits are then adjusted so that no current flows in either galvanometer. It can easily be shown that the following relations then hold:

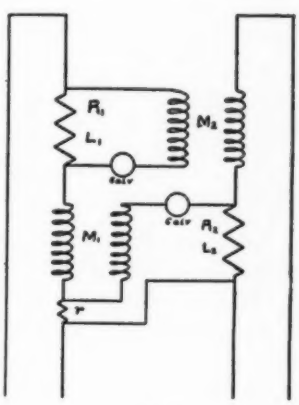

Fig. 1

$$R_1R_2 = p^2(M_1M_2 + L_1L_2) \qquad (1)$$

$$\frac{pL_1}{R_1} + \frac{pL_2}{R_2} = \frac{prM_2}{R_1R_2} \quad \text{or} \quad \frac{r}{pM_1} \quad \text{very closely,} \qquad (2)$$

where $p = 2\pi \times$ frequency. The first of these equations can be used in the absolute measurement of resistance and the second gives a measure of the sum of the phase angles of the two resistances.

This method requires (1) that the mutual inductances be pure, *i. e.*, give e.m.f.'s in exact quadrature with the primary current, (2) that the frequency be

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, April 24–25, 1914.

held very constant during the measurement and (3) that the current be sinusoidal or that the detectors be sufficiently selective to the fundamental frequency.

The second method makes use of a standard whose resistance can be changed without changing its inductance. This can be done for example by using a copper standard whose temperature can be varied. Then if the observed decrease in phase angle be $\Delta\theta$ and the corresponding proportional increase in resistance be a we have

$$\frac{pL}{R} = \frac{1+a}{a}\Delta\theta \tag{3}$$

This method requires merely an accurate measurement of the change in the phase angle.

In order to test the practicability of these methods the authors have made measurements on four low resistances. First, all of the six possible sums were measured directly by the first method. The phase angles of the individual standards at 60 cycles are given in Table I. These four values satisfy the six observations to within two minutes.

TABLE I.

Designation.	Resistance.	Phase Angle.
C	.000337 ohm	29.0′
K	.01 ohm	2.5′
R	.001 ohm	19.0′
S	.001 ohm	16.5′

Measurements by the second method on the copper standard (C), using a temperature rise of about 60° C., gave a phase angle of 30.5 minutes. This value agrees fairly well with the value given above.

To get further checks on the results several differences of the phase angles were determined by an independent method. The observed differences and those computed from the values in Table I. are given in Table II. below.

TABLE II.

Designation.	Differences Observed.	Computed.
$R-S$	1.9′	2.5′
$C-R$	10.1′	10.0′
$R-K$	14.8′	16.5′

It is interesting to note that accurate calculations assuming uniform current distribution give $C = 24.1$ minutes and $K = .8$ minute.

The above results indicate the methods to be entirely practicable and it is thought that by taking further precautions as to frequency control, purity of mutual inductance and sensitivity a precision of several tenths of a minute can be obtained.

Effect of Residual Gases on Contact E.M.F.'s and Photo- Currents.[1]

By R. A. Millikan and W. H. Souder.

CURVES representing both the variation of contact E.M.F.'s and saturation photo currents with time have been taken on freshly cut sodium surfaces both in the best vacuum obtainable with a Gaede molecular pump and in vessels containing residual gases.

The most striking characteristics of the photo-current-time curves is that they are of altogether different form according as the frequency of the light with which they are taken is that of the extreme ultra-violet or that of the visible spectrum. Thus, when tested with light of wave-length 5,461 Å. the photo-sensitiveness of a *freshly cut* sodium surface is zero. It rises with time to a considerable value and finally falls again to zero When tested, however, with light of wave-length 2,535 Å., this same surface shows a large initial photo-sensitiveness which falls off steadily with time to zero.

These photo current-time curves taken in connection with the contact E.M.F.-time curves are interpreted as follows:

A freshly cut sodium surface is not sufficiently electro-positive to respond photo-electrically to light of wave-length 5,461 Å., but under the influence of an active gas, the sodium forms a new substance which is more electro-positive than the freshly cut sodium and hence is photo-sensitive to longer waves. The photo-curve taken with wave-length 5,461 Å. represents then merely the growth and decay of this substance. For sufficiently short waves, however, the freshly cut surface is itself so photo-electrically active that its own decay curve completely masks the rise and fall curve due to the growth and decay of the more electro-positive substance resulting from the action of gas upon the sodium.

In view of these results the authors raise a question as to the correctness of the conclusions of Wiedmann and Hallwachs[2] that photo currents are only obtainable in the presence of gas. We suggest that if the Wiedmann and Hallwachs experiments are repeated with light of sufficiently short wave-lengths instead of with visible light, it is not likely that the photo-sensitiveness will be found to vanish in the way in which it did in the experiments reported by these authors. Further experiments on potassium and lithium are in progress.

A Direct Determination of "h."[1]

By R. A. Millikan.

THE experiments herewith reported were undertaken for the sake of subjecting to rigorous experimental test the three assertions contained in Einstein's photo-electric equation[3]

$$\tfrac{1}{2}mv^2 = PDe = h\nu - P.$$

These assertions are

[1] Abstract of a paper presented at the Washington meeting of the Physical Society, April 24, 1914.

[2] Ber. d. D. Phys. Ges., 16, 107, January 30, 1914.

[3] A. Einstein, Ann. d. Phys. (4), 20, 199, 1905.

1. That there is a linear relation between the frequency of the impressed light and the maximum energy of emission of the electrons ejected by it.

2. That the slope of the line representing the linear relation between PD and ν is h/e, *i. e.*, that this slope times e is Planck's "h."

3. That the intercept of the PD line on the ν axis gives the frequency ν_0 at which the metal in question first begins to be photo-electrically active.

The second and third of these assertions have not heretofore been made the subject of accurate test nor can they be so made without simultaneous measurement *in vacuo* of both contact potentials and photo-potentials in the case of metals which are sensitive throughout a long range of frequencies. The spectral lines used in the test must further be strictly monochromatic and of frequency determinable with a high degree of precision.

The first of the assertions of Einstein's equation has previously been tested with widely varying results by Ladenburg,[1] Kunz,[2] Hughes,[3] Richardson and Compton,[4] and Cornelius.[5] The most satisfactory of these measurements are probably those of Richardson and Compton, though Pohl and Pringsheim[6] do not regard even these as sufficient to distinguish between $PD \propto \nu$ and $PD \propto \nu^2$, much less to test between any closer relations such as $PD \propto \nu$ and $PD \propto \nu^3$, the latter being the relation implied by Lindemann's theory. Very recent measurements made in the Ryerson Laboratory by Kadesch[8] between $\lambda = 3{,}900$ and $\lambda = 2{,}300$ seem however to speak positively in favor of a proportionality between PD and ν. The present measurements made on sodium from $\nu = 6{,}800$ to $\lambda = 2{,}300$ fully confirm Kadesch's linear relationship and further, they fix the value of the slope, *i. e.*, of h/e at 4.123×10^{-15} volt/frequency with an error of not more than $\frac{1}{2}$ per cent.

Inserting the author's value of e, viz., 4.774×10^{-10} which is thought to be correct to within .2 per cent., there results from this value of h/e

$$h = 6.561 \times 10^{-27}.$$

This value of "h" combined with the author's value of e gives with the aid of Planck's equation the following value for the constant of total radiation

$$\sigma = 5.688 \times 10^{-5},$$

which is very close to the value obtained by Coblentz[9] from a study of all the data at present available.

When this value of σ is combined with the author's value of e and substitution made in Planck's equation, the Planck-Wien constant of spectral radiation

[1] E. Ladenburg, Verh. d. D. Phys. Ges., 9, 504, 1907.
[2] J. Kunz, PHYS. REV., 29, 212, 1909; also 33, 208, 1911.
[3] A. L. L. Hughes, Phil. Trans., 212, 205, 1912.
[4] O. Richardson and R. T. Compton, Phil. Mag., 24, 575, 1912.
[5] D. W. Cornelius, PHYS. REV., 1, 16, 1913.
[6] R. Pohl u. P. Pringsheim, Verh. d. D. Phys. Ges., 15, p. 637, 1913.
[7] F. A. Linderman, Verh d. D. Phys. Ges., 13, 1107, 1911.
[8] W. H. Kadesch, PHYS. REV., May, 1914.

is found to be

$$c_2 = 1.434$$

which is within one part in 700 of the latest Reichsanstalt value of this constant.

The value of ν_0 obtained for sodium, the metal upon which all of these experiments have been made, is $.439 \times 10^{15}$, which corresponds to $\lambda = 6{,}800$.

Planck's constant "h" is thus found to stand out in connection with photoelectric measurements, perhaps more sharply, more exactly, and more certainly than in connection with any other type of measurements thus far made.

ERRATUM.

Page 486, Vol. III., No. 6, Second Series, lines 13 and 12 from the bottom of the page, in the abstract of a paper by G. W. Middlekauff and J. F. Skogland, entitled "Characteristic Curves of Tungsten Filament Incandescent Lamps and Their Application in Heterochromatic Precision Photometry," should read as follows: x = log per cent. voltage and y = log per cent. candlepower, log per cent. watts, log per cent. current, or log actual watts per candle."

Through typographical error, in the printed text, "cent." after "per" was omitted in four places.

NEW BOOKS.

Vorlesungen Über die Theorie der Warmestrahlung. By DR. MAX PLANCK. Leipzig: Johann Ambrosius Barth, 1913. Pp. xii + 206. Price, Mk. 7.

There is no doubt that the first edition of this volume of Planck's, and the articles which preceded it, have been the most stimulating contributions to physical literature of many decades, and since the second edition involves some radical changes in the point of view it is of fresh interest and importance.

The characteristic feature of the quantum hypothesis as used in the first edition to deduce the energy distribution law for a black body or perfect radiation was this, that the energy content of a resonator must always be an integral multiple of energy ϵ, whose magnitude depended on the frequency of the resonator, being $h\nu$, where ν is the frequency of the resonator and h is the quantum or unit of activity introduced by Planck. This idea of integral energy-content involved the further hypotheses of discontinuous absorption and emission of radiant energy on the part of the resonator. The commonly accepted idea of the early quantum theory seems to be that this discontinuity of absorption and emission necessarily involves the idea of attributing a granular *structure* to radiant energy in space. This is not necessary however, and the discontinuous behavior might better be attributed to a peculiarity of resonator (atomic) structure. In the second form of the quantum theory of radiation as presented in this new edition, and the articles on which the revision is based, the hypothesis of discontinuous changes in energy content is given up, absorption is supposed to be a continuous process taking place according to the ordinary laws of electro-dynamics, while emission is still considered as discontinuous. It is supposed that a resonator can only emit when its energy content is some integral multiple of $\epsilon = h\nu$. When emission occurs the resonator loses all of its energy, and the probability of emission actually occurring at the possible times is determined by a probability function which increases as the energy content increases. This change in the point of view, as well as an article of Planck's which has appeared subsequent to the publication of this second edition of his lectures, makes still more evident that the quantum theory is really a theory of resonator structure, or atomic structure, if it is to be extended to anything beyond Planck's ideal resonators. The fundamental hypotheses as to the relation between entropy and probability, and the definition of probability remain as in the first edition, but the new point of view necessitates an entire rediscussion of the relation between the mean energy and entropy of a group of resonators. The restriction that energy interchange occurs only between resonators of the same frequency, so that the resonators as a whole would not of themselves assume a particular equilibrium distribu-

tion of energy, still holds as in the first treatment, though in the later article above referred to Planck suggests one way of removing this restriction. The outcome of the whole discussion is the well-known Planck law of energy distribution.

Planck was led to the change in hypotheses which we have just outlined because the hypothesis of discontinuous absorption seemed unreasonable. A skeptic might question whether discontinuous absorption is any more unreasonable than discontinuous emission—or indeed whether "reasonable" and "unreasonable" have any meaning whatever in connection with much of the present day discussion, but there is no doubt of the clearness and frankness with which Planck has stated his hypotheses. Nor does there seem to be any doubt that he has introduced a constant "h," which is of far-reaching significance, whatever that significance may be, and the tremendous stimulating power of his ideas is evident to every one. C. E. M.

Electric Arcs. Experiments upon arcs between different electrodes in various environments and their explanation. By C. D. CHILD, Professor of Physics at Colgate University. The D. Van Nostrand Co. 5×7, cloth, 203 pp., 58 illustrations. $2.00.

This book deals with the arc primarily from the point of view of pure science rather than that of industry, though its conclusions have a practical as well as a scientific interest. It is a well-written, careful presentation of the often conflicting results of many investigators, made by one who has himself carried out important researches in this field. Though fifteen years have passed since Mrs. Ayrton's book on "The Electric Arc," our knowledge of it is still in many respects incomplete and unsatisfactory. Hence, instead of giving "a brief and definite statement of the laws governing the action of the arc," the author has been compelled, as he says, to present "an extended review of what different experimenters have thought about these laws," and, where the laws are unknown, to "discuss the results of those who have endeavored to find them." Such a method is likely to lead to a wearisome collection of details; but in this case the discussion is ably conducted, terse and constructive. Hundreds of references to original articles make the book especially valuable to future investigators. To most of us the final chapter on the theory of the arc is of chief interest. The author's conclusions as to the mechanism of the arc, though largely unproved by experiment, yet seem to follow convincingly from the preceding analysis of available data. They give the most complete and suggestive explanation of the phenomena so far advanced. G. S. F.

UNIVERSITY OF WISCONSIN.

Rays of Positive Electricity and Their Application to Chemical Analyses. By SIR J. J. THOMSON. New York: Longmans, Green and Co., 1913. Pp. vi + 129. Price $1.40.

This volume is one of a series of monographs on physics edited by Sir J. J. Thomson, O.M., F.R.S., and Frank Horton, D.Sc. It contains an account

of the earlier experiments by Goldstein, Wien, and others, on anode or positive rays and also of the later ones in this same field by Sir J. J. Thomson himself. Full descriptions are given of the various types of apparatus used to investigate the properties of these rays. Accounts are given of the experiments which established the existence of multiply charged atoms, of allotropic forms of neon and of hydrogen, and of the molecular groupings represented by CH, CH_2, and CH_3. Reference is also made to the Doppler effect observed by Stark, Steubing, and Wendt in their investigations of the spectra of positive rays. The book concludes with a description of Sir J. J. Thomson's latest experiments on the evolution of helium and neon by substances bombarded by cathode rays. The work is full of suggestions and will prove a valuable aid to those following or wishing to become familiar with the manner in which positive rays have been used to add to our knowledge of the ultimate structure of matter.

J. C. M.

Recent Physical Research. By DAVID OWEN. London: The Electrician Printing and Publishing Co., 1913. Pp. i + 156. Price 3s. 6d.

This volume, which is a reprint of a series of articles published in the Electrician, aims at giving an account of a number of the more important of the recent advances in physics. The subjects dealt with are (1) rays of positive electricity and their applications to chemical analysis by Sir J. J. Thomson, (2) Rutherford's and Geiger's method of counting the alpha particles, (3) the work of Curie, Langevin, and Weiss, in developing a theory of magnetism, (4) Birkeland and Störmer's theory of the origin of auroræ, (5) the Brownian movement as investigated by Perrin, (6) the pressure of radiation, (7) Rubens, work on very long infra-red rays. (8) determinations of the wave-lengths of Röntgen rays, (9) the electron theory of conduction in metals, and (10) Heusler's aluminium-copper-manganese magnetic alloys. The various accounts are written with care and accuracy and the book should be useful to those for whom the original papers are not accessible. Subjects which might have been included in the book with advantage are: Paschen's work on series spectra, and the contributions of Wood, Lenard, and others, to our knowledge of phosphorescence and fluorescence phenomena. J. C. M.

Die Theorie der Strahlung und der Quantum. Verhandlungen auf einer von E. Solvay einberufenen Zusammenkunft (30. Oktober bis 3. November 1911). Edited by A. EUCKEN. Halle: Wilhelm Knapp, 1914. Pp. xii + 405. Price Mk. 15.60.

This book is the counterpart in German of the French report of the Solvay conference which was published in 1912 by Langevin and de Broglie. Eucken has added a valuable appendix giving an account of the development of the quantum theory down to the summer of 1913. The papers presented at this conference are of the highest order. H. A. Lorentz discusses the application of the equipartition of energy to radiation. Jeans presents the kinetic theory of specific heat by Maxwell's and Boltzmann's methods. Warburg describes

experiments to verify Planck's formula for normal radiation and Rubens describes experiments with long waves. Planck discusses the laws of radiation and the quantum hypothesis; Knudsen, the kinetic theory and the properties of the ideal gas; Perrin, the proof of the existence of molecules. Nernst applies the quantum theory to physical and chemical problems. Kamerlingh Onnes deals with electrical resistance. Sommerfeld applies the quantum theory to radiant pulses. Langevin presents the kinetic theory of magnetism. Einstein discusses specific heats. Lord Rayleigh contributes a short letter. Other leaders of modern physics, Rutherford, Mme. Curie, H. Poincaré and others, took part in the discussions. The book is of the greatest interest and importance.

W. F. M.

Physikalische Chemie der homogenen und heterogenen Gasreaktionen unter besonderer Berucksichtigung der Strahlungs- und Quantenlehre sowie des Nernstschen Theorems. By DR. KARL JELLINEK. Leipzig: S. Hirzel, 1913. Pp. xiv + 844. Price, Mk. 32.50.

This book contains much more than its name indicates. It opens with a study of Carnot's cycle and in the first two hundred pages there are given a development of the more modern thermodynamics, so far as it is needed in the applications to gases, and a sketch of the kinetic theory of gases. Nernst's principle of thermodynamics is considered in this portion of the book from its relations to entropy. Over one hundred and fifty pages are then given to an exposition of the theory of radiation and over one hundred pages more to the study of the relations of the theory of radiation to the theories of specific heats, of heats of reaction, and to Nernst's principle. The experimental work connected with the foregoing theories is described in two hundred pages more. The last hundred pages deal with the electrochemistry and the photochemistry of gases. The physical chemistry of gases takes up but a small part of the book. The author has studied his subject fully, he gives careful criticisms of the points of difficulty which occur so often in these modern theories, and has made a book which will be very useful for study and for reference.

W. F. M.

Die Entwickelung des Temperaturbegriffs im Laufe der Zeiten. By K. MEYER. Braunschweig: Vieweg and Sohn, 1913. Pp. 1 + 160. Price, Mk. 4.

The greater part of this small volume is devoted to the development of the concept of heat and temperature from the invention of a thermometer (about 1610) to the introduction of the Kelvin absolute thermodynamic scale. A very brief introductory chapter merely sketches the earlier peroid, before Galileo, and an equally brief final chapter states, in very good form, the hypotheses on which our present measurements rest, indicates the thermodynamic connection between the Kelvin scale and a gas scale, and gives a few results of measurements at extreme low temperatures. The main body of the book is well indexed and full of references, but is more largely concerned, of necessity, with quaint ideas than with important logical developments. No mention is made of the

growth of the kinetic theory of matter in its relation to temperature, not of the relation of radiation theory to temperature, though both of these are of fundamental importance in the development of the concept. C. E. M.

Optique Geometrique. By J. BLEIN. Paris: Octave Doin et Fils, 1913. Pp. vi + 263. Price, 5 Fr.

The usual topics of geometric optics are clearly and briefly treated in this small volume. Of the eleven chapters three are devoted to the general subject of image formation, three to the general discussion of optical instruments, as to their magnifying power, field, resolving power, focal surface and brightness, and three to the more detailed discussion of aberrations and the characteristics of various types of objectives. There are enough diagrams to make the treatment clear, and the usefulness of the book is increased by an index and bibliography. C. E. M.

Researches in Color Vision and the Trichromatic Theory. By SIR WILLIAM DE W. ABNEY. New York: Longmans, Green and Company, 1913. Pp. x + 418.

As stated by the author in his preface, this book was written with a two-fold purpose, namely: to make his published contributions (extending over twenty-five years) more conveniently accessible; and, "to show that the trichromatic theory of color vision does not yet require a funeral oration over its remains."

It is divided into two parts, of which the first, comprising one third of the book, has been the subject of lectures to students. A general introductory chapter is followed by one on the eye and another on phenomena in vision. A description of measuring instruments is then followed by a chapter on the intensity of spectrum colors and one on their relative brightness or "luminosity." With a chapter on each of the subjects: "Complementary and Contrast Colors," "Numerical Registration of Colors," and "Color Disks," the first part is completed. Part II. opens with an interesting chapter on Extinction of Color and Light—a corresponding laboratory investigation of the commonly observed change in hue, as the day closes, of bright-colored flowers and foliage. This is followed by another on "Color Fields"—the areas on the retina capable of distinguishing the various colors—after which the author turns his attention to the theory of color vision and the various experimental observations incident to this study, of which that on color blindness occupies a large part. The style is lucid and the typographical effect pleasing. C. A. S.

Les Propriétés Optiques des Solutions. By C. CHÉNEVEAU. Paris: Gauthier-Villars, 1913. Pp. vii + 240.

This is essentially a second edition of the author's work entitled Recherches sur les propriétés optique des solutions et des corps dissous. It is of value to the physicist who is especially interested in the optical properties of solutions, and to the chemist who seeks a knowledge of chemical composition of bodies by means of their optical properties.

The first two chapters are devoted to a critical presentation of the theories of refraction and dispersion including those of Havelock and Langevin—the most recent. The next three present the results of the experimental study of refraction and dispersion of aqueous solutions (and mixtures) of inorganic substances, and also of those not entirely aqueous. Chapter VI., of special interest to chemists, deals with the determination of the chemical composition of organic substances by means of their optical constants. The book closes with a chapter, uniquely placed, on apparatus and methods of measurement. The large bibliography at the end shows the vast amount of work which has been done in this and closely allied fields. C. A. S.

Medizinische Physik. By PROF. DR. OTTO FISCHER. Leipzig: S. Hirzel, 1913. Pp. xx + 1120. Price Mk. 36.

This voluminous work attempts to develop those somewhat advanced principles of physics which lie beyond the scope of the ordinary elementary text, but which are indispensable from the point of view of the advanced student of medicine. The method of treatment while aiming to be non-mathematical involves quite freely the differential calculus, but not the integral. The various subjects are developed solely from examples of their application in the animal body. For instance the the center of motion ofgravity of the human body in walking serves as a basis about which to develop ideas of composition of velocities and accelerations, their tangent and normal components and methods of graphical representation including the hodographs. Rotations are taken up in connection with linkages and the detailed analysis of the motions of the arms and the legs is given. The humero-radial linkage serves to introduce the idea of instantaneous axis of rotation and generalized coördinates are used.

Under the excellent title of Muscle Mechanics are introduced the various ideas of mass and force. The composition of forces, and moments with the resulting effects of motion, rotatory and translatory, with reference to the center of mass are studied from examples of various muscle and bone combinations familiar to the anatomist.

In acoustics the development of the fundamental principles of wave motion and the applications to sound, together with Fourier's analysis, quite obviously, has nothing to do with the human body. An elaborate treatise of the physical phenomena occurring in the ear, its structure, theories of audition and the mechanism of the production of speech makes this section in keeping with the general plan.

Optics from the geometrical standpoint is handled at great length, occupying about five hundred pages. The applications of the laws of reflection and refraction not only to the human eye but to lenses of all sorts, the telescope, the microscope in great detail—together with general considerations of the lens errors, astigmatism, spherical and chromatic aberrations, go rather far afield from the general plan of confining attention to the human body. The Abbe theories of image formation, ultramicroscopy and the applications of polarized light to the polarization microscope and the polarimeter conclude this division and the entire work.

Of the tremendously important applications of electricity to modern applied physics and to medicine no mention is made whatever, it being suggested in the preface that medical men are better informed in these directions.

H. B. L.

UNIVERSITY OF CHICAGO.

Bausteine zur Flugbahn-und-Kreisel Theorie. By AUGUST DAHNE. Berlin, R. Eisenschmidt, 1914. Pp. i + 44.

This monograph is of primary interest to students of ballistics. Its author, an army officer, assuming familiarity with the gyroscopic properties of projectiles comments on the causes of the well-known deviations of the axis of rotation. Having previously demonstrated that in tops these deviations are caused primarily by friction effects on the axis, in this pamphlet he shows that for projectiles too the air friction (Magnus effect), is the true cause and that the experimental facts brought out during the last 36 years are in accord with this and do not bear out the Poinsot theory which is based on the principle of infinitely small rotations.

H. B. L.

UNIVERSITY OF CHICAGO.

Optique Physique. By R. W. WOOD. Translated from English by H. VIGNERON and H. LABROUSTE. In two volumes: Tome I. Optique Ondulatoire (translated by H. Vigneron), 1913; Tome II., Étude des Radiations (translated by H. Labrouste), 1914. Paris, Gauthier-Villars.

This is a careful translation of the second edition of Professor Wood's excellent treatise. Being spread over two volumes, the translation makes a much more pleasing typographical effect than that of the somewhat congested single volume of the original. Several paragraphs of new matter by the author, dealing principally with fluorescence and resonance spectra of vapors, appeai in the second volume.

C. A. S.

Elements of the Precision of Measurements and Graphical Methods. By H. M. GOODWIN. New York: McGraw-Hill Book Company, 1913.

This is an elementary treatise of experimental errors and graphical methods for technical students. It will be found a very good presentation for those who believe in the applicability of the method of least squares to technical subjects.

C. A. S.

The Chemistry of the Radio-Elements. By FREDERICK SODDY, F.R.S. New York: Longmans, Green and Co., 1914. Pp. i + 46. Price, $ .60.

This brief monograph brings together a number of the more recent experimental contributions to our knowledge of the radio-elements. In attempting to fit all the known radio-elements into the periodic table the author brings forward the view that "isotopism" exists in nature and that as a consequence a number of the radio-elements being chemically non-separable are practically

identical. The work includes chapters on the origin of actinium, the nature of the end products in radioactive disintegration, the structure of atoms, and the nature of the Argon gases. The work concludes with an extended list of references to recent papers on the subjects discussed. J. C. M.

A New Era in Chemistry. By HARRY C. JONES. New York: D. Van Nostrand Company, 1913. Pp. xii + 326. Price $2.00.

This work, attractively written, is a popular presentation of the advances which have been made in the different branches of chemistry in the last quarter of a century. The various subjects treated are given an historical setting and the book abounds with references of a personal nature which throw considerable light on the methods followed by the different investigators. The work contains chapters on the Law of Mass Action; the Development of Stereochemistry; the Phase Rule; Chemical Equilibrium; Osmotic Pressure; Electrolytic Dissociation; the Theories of Solution, Colloidal Chemistry; Ionization of Gases and Radiochemistry. In the treatment of these subjects the fundamental character and the scope of the contributions made by Van't Hoff, Arrhenius, Willard Gibbs, Ostwald, and J. J. Thomson are all clearly and well portrayed. J. C. M.

A First Course in Physics. (Revised Edition.) By R. A. MILLIKAN and H. G. GALE. New York: Ginn and Company, 1913. Pp. x + 442. Price, $1.25.

The changes which have been made in the revised edition of this little book include a number of interesting features. The list of portraits inserted has been extended to include a few of the more eminent of modern physicists. The portions dealing with mechanics and the principles underlying the dynamo and motor have been simplified, and in light more emphasis has been laid upon a combination of the wave and the ray methods in the treatment of image formation. In the interpretation of the phenomena of molecular physics frequent use is made of the kinetic theory of matter and of the atomic or electronic theory of electricity. Altogether the book constitutes an admirable introduction to the study of physics. J. C. M.

Geometrical Optics. By A. S. PERCIVAL. New York: Longmans, Green and Co., 1913. Pp. vi + 132. Price, $1.50.

Students and others desiring what may be called an intermediate treatment of geometrical optics will find this book exceedingly useful. In developing the subject the author has omitted all reference to matters of purely academic interest and has confined his treatment to those phases of the subject which are more especially capable of practical application. The proofs given are concise and the sequence is excellent. The numerical illustrations of the various formulae used in the book constitute a particularly attractive feature.

J. C. M.

First Course in Algebra. By W. B. FITE. Boston: D. C. Heath and Co., 1913. Pp. v + 285. (*Received.*)

Die Brownsche Bewegung und Einige Verwandte Erscheinungen. By G. L. DE HAAS-LORENTZ. Braunschweig: Vieweg and Sohn, 1913. Pp. i + 103. Price, Mk. 3.50.

Previous books on Brownian movements have been primarily reports from certain experimenters upon their own experimental results. The book before us, which grew out of a Doctor's thesis, is a very valuable summary of most of the important *theoretical* as well as experimental researches on Brownian Movements which have appeared up to the present time. It is invaluable for a student of this subject. Indeed I know of no other book in which the subject is treated in any such thoroughgoing way. The original features are mainly in the latter chapters and consist (1) in the discussion of the relation between the actual, complicated Brownian movement and the visible motion of the Brownian particle, and (2) in certain additions to the theoretical study of the spontaneous transport of Electricity by Heat.

R. A. M.

Photo-Electricity. The Liberation of Electrons by Light with Chapters on Phosphorescence, Photo-chemical Actions and Photography. By H. STANLEY ALLEN, M.A., D.Sc. London: Longmans Green & Co. Pp. i + 216. Price, $2.10.

The task of correctly portraying the present status of photo-electric research is a very difficult one, for the reason that, though the papers which have appeared in this field may be numbered literally by the thousand, there is as yet no unified and consistent theory in the light of which all the phenomena of Photo-electricity may be interpreted. How then is an author to choose between conflicting results and present only material which is of real significance? Or, if he strives to be quite impartial, how is he to avoid making his book a mere compendium of disconnected researches and of irreconcilable view-points?

Dr. Allen has met these inherent difficulties with notable success. He shows a thorough familiarity with the whole of the literature and at the same time he has shown much judgment in sifting it out and in getting each research into some sort of a theoretical setting. The chapters which present the relations to the Electron Theory of the phenomena of Fluorescence, Photochemistry and Photography are particularly valuable.

The fact that it takes a book of 216 pages to present at all adequately a subject as new and as undeveloped as is Photo-electricity shows with what amazing rapidity Physics is growing at the present time.

R. A. M.